Fall 2014

Energy analysis of cool, medium, and dark roofs on residential buildings in the U.S.

Michael A. Dunbar
Purdue University

Graduate School Form 30
(Revised 08/14)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis/Dissertation Acceptance

This is to certify that the thesis/dissertation prepared

By Michael Alan Dunbar

Entitled
ENERGY ANALYSIS OF COOL, MEDIUM, AND DARK ROOFS ON RESIDENTIAL BUILDINGS IN THE U.S.

For the degree of Master of Science

Is approved by the final examining committee:

Dr. Robert Herrick

Dr. Gareth O'Donnell

Dr. Michael J. Dyrenfurth

Dr. Rajeswari Sundararajan

To the best of my knowledge and as understood by the student in the Thesis/Dissertation Agreement, Publication Delay, and Certification/Disclaimer (Graduate School Form 32), this thesis/dissertation adheres to the provisions of Purdue University's "Policy on Integrity in Research" and the use of copyrighted material.

Approved by Major Professor(s): Dr. Robert Herrick

Approved by: Dr. James Mohler 10/16/2014

Head of the Department Graduate Program Date

ENERGY ANALYSIS OF COOL, MEDIUM, AND DARK ROOFS ON RESIDENTIAL BUILDINGS IN THE U.S.

A Thesis

Submitted to the Faculty

of

Purdue University

by

Michael A Dunbar

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science

December 2014

Purdue University

West Lafayette, Indiana

To my family and friends

ACKNOWLEDGEMENTS

I would like to thank my committee for their tremendous efforts in helping me with this thesis.

Thanks to Dr. Gareth O'Donnell for ensuring that I knew and understood each part of the thesis thoroughly and also challenging me every step of the way. Sometimes, it was frustrating but I have grown to appreciate the critiques and am pleased to have had you on my committee.

Thanks to Dr. Rajeswari Sundararajan for the talks about life and also focusing on maximizing my potential both in school and for my career. I appreciated the critiques about critical portions of my thesis. I cannot thank you enough for the help.

Thanks to Distinguished Professor Robert Herrick for guiding the process for my thesis and ensuring that I met core deadlines for my thesis and stayed onboard with the deadlines at Purdue while abroad in Spain or in Ireland.

Thanks to Dr. Michael Dyrenfurth for stepping in as an additional member to my committee due to emergency circumstances. Your help was greatly appreciated in the entire process of the thesis.

I also want to thank all of the different professors at Purdue and Dublin Institute of Technology that helped me along the way with my thesis. Without your help, this would have been significantly more difficult to achieve.

TABLE OF CONTENTS

Page

Page

Page

LIST OF TABLES

Table Page

Appendix Table Page

Appendix Table Page

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

ANSI – American National Standards Institute

ASHRAE – American Society of Heating, Refrigerating, and Air-Conditioning Engineers

BA- Building America

BAHSP – Building America House Simulation Protocol

BC3 - Building Component Cost Community Database

BER – Building energy rating

BECP - Building Energy Codes Program

CDD - Cooling degree days

DIY - Do-it-yourself

DOE – U.S. Department of Energy

EIA – U.S. Energy Information Agency

EPA – U.S. Energy Protection Agency

EERE – U.S. Office of Energy Efficiency & Renewable Energy

GCCA – Global Cool Cities Alliance

HDD - Heating degree days

HVAC – Heating, ventilation and air conditioning

ICC – International Code Council

IDF – EnergyPlus input data file

IECC – International Energy Conservation Code

IESNA – Illuminating Engineering Society

IPMVP – International Performance Measurement and Verification Protocol

IRC – International Residential Code

kWh -- Kilowatt-hours

LEED - Leadership in Energy and Environmental Design

MEC -- Model Energy Code

NPV – Net Present Value

NREL - National Renewable Energy Laboratory

PC - Photo catalyst coating

PNIPAM – Poly (N-isopropyl acrylamide)

PNNL -- Pacific Northwest National Laboratory

PV – Photovoltaic

RECS -- Residential energy consumption survey

SPP – Simple Payback Period

SRI - Solar reflective index

TMY3 – Typical Meteorological Year

ABSTRACT

Dunbar, Michael A. M.S., Purdue University, December 2014. Energy Analysis of Cool, Medium, and Dark Roofs on Residential Buildings in the U.S. Major Professors: Dr. Robert Herrick and Dr. Michael Dyrenfurth.

This study reports an energy analysis of cool, medium, and dark roofs on residential buildings in the U.S. Three analyses were undertaken in this study: energy consumption, economic analysis, and an environmental analysis. The energy consumption reports the electricity and natural gas consumption of the simulations. The economic analysis uses tools such as simple payback period (SPP) and net present value (NPV) to determine the profitability of the cool roof and the medium roof. The variable change for each simulation model was the roof color. The default color was a dark roof and the results were focused on the changes produced by the cool roof and the medium roof. The environmental analysis uses CO_2 emissions to assess the environmental impact of the cool roof and the medium roof. The analysis uses the U.S. Department of Energy (DOE) EnergyPlus software to produce simulations of a typical, two-story residential home in the U.S. The building details of the typical, two-story U.S. residential home and the International Energy Conservation Code (IECC) building code standards used are discussed in this study. This study indicates that, when material and labor costs are assessed, the cool roof and the medium roof do not yield a SPP less than 10 years. Furthermore, the NPV results assess that neither the cool roof nor the medium roof are a

profitable investment in any climate zone in the U.S. The environmental analysis demonstrates that both the cool roof and the medium roof have a positive impact in warmer climates by reducing the CO_2 emissions as much as 264 kg and 129 kg, respectively.

CHAPTER 1. INTRODUCTION

Humans are definitely living in the electronic age. Energy consumption is at an all-time high due to the utilization of electronics, televisions, and many other devices in the home. This has presented new challenges and there is a move to discover new energy efficient strategies which will hopefully reduce our energy usage.

One of the most recent energy strategies is the cool roof. The cool roof is a roof with a low solar absorptivity level that is designed to reduce the air conditioner costs for buildings during the cooling load season. Recently, it has been noted that if cool roofs were implemented nationally, it would reduce the global warming trend by two years. Furthermore, cool roofs are viewed as a cost-saving measure. However, there are no studies that have factored in external costs, such as the material and labor costs. Also, the environmental impact has been stated, but there has not been any publicly available data that has demonstrated how the positive environmental impact of cool roofs was determined. Therefore, the Net Present Value (NPV) was taken into account to determine whether the investment of a cool roof is profitable for a residential homeowner.

Little research has been performed to evaluate whether cool roofs are a better option than other roof types, such as a medium-colored roof. Most of the research has been focused on commercial buildings and low-sloped roofs. .

Figure 1.1 breaks down all the different climate zones in the U.S., according to the IECC (IECC, 2014). Therefore, this study focused on a nationwide analysis to determine the impact of cool roofs and medium roofs on residential homes of each climate zone within the U.S.

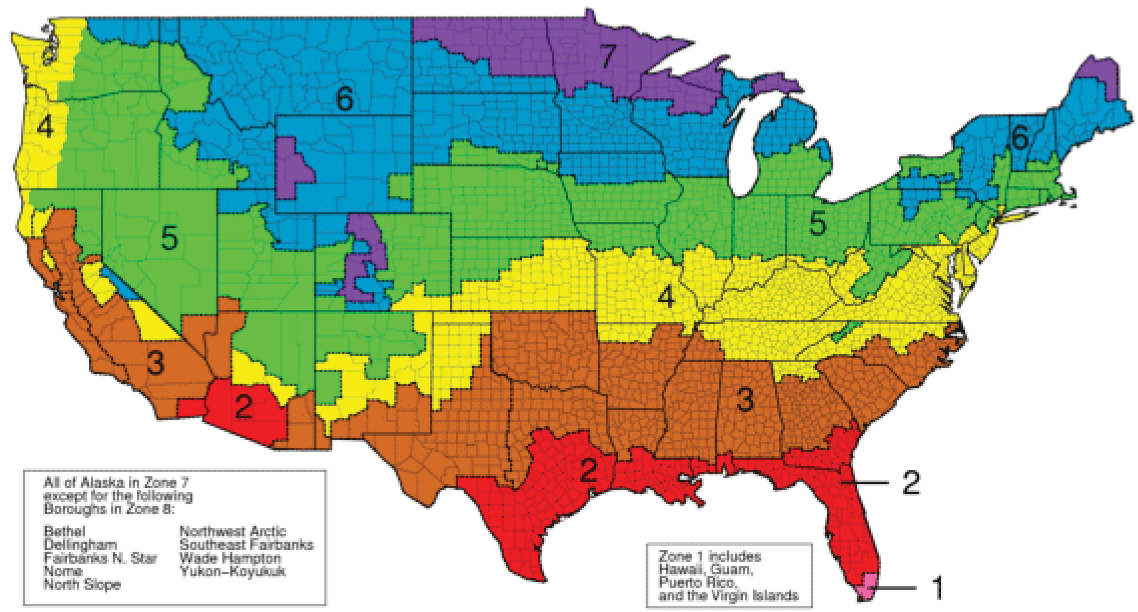


Figure 1.1 2009 IECC climate zones map (IECC, 2014)

Many homeowners are looking for ways to reduce their energy costs. Leadership in Energy and Environmental Design (LEED), ENERGY STAR, Building America, and other programs have been used to help residential homeowners with decision making related to energy efficiency in the home (EERE, 2008).

A major problem is that few studies have used verified simulation models. Therefore, the simulation program used in this study was the EnergyPlus software, which is backed by the DOE. This simulation model was based on the residential building codes established by the International Energy Conservation Code. The 2009 IECC version was used because it was established as the benchmark prototype model in the DOE article “Building America House Simulation Protocols” (Hendron et al., 2010).

The EIA reports that buildings in the U.S. are responsible for 40% of the country’s CO_2 emissions. Furthermore, buildings in the U.S. produce 8% of the world’s CO_2 emissions. Residents in homes built between 2000 and 2009 consumed 19% more energy than residents in homes built in the 1980s (EIA, 2010). Therefore, this study focused on the CO_2 impact due to the roof color and the potential CO_2 savings or losses when the roof color has been changed from a dark roof color to a light roof color or a medium roof color.

1.1 Problem statement

An energy analysis was conducted on changing the roof color on a residential home to determine the potential energy savings, return on investment as well as the environmental impact in each climate zone in the U.S.

1.2 Primary research questions

Does the residential home produce energy savings when the dark roof is replaced with either a cool roof or a medium roof in the respective U.S. climate zone?

Does the residential home produce less CO_2 emissions when the roof color is changed from a dark roof color to a medium or a cool roof color?

Does a cool roof and a medium roof be positive investments when material and labor costs are incorporated over a 10-year period?

1.3 Significance

This study sought to further the research by doing a full-year energy analysis on a cool roof and a medium roof rather than three months in the summer. Furthermore, there are not any articles that discuss how cool roofs financially comparewhen material and labor costs are taken into account in the economic analysis. This study also incorporated a medium-color roof to determine whether it fares better than the cool roof. This study also assessed the environmental impact by recording the amount of CO_2 emissions saved when the cool roof and the medium roof were implemented.

1.4 Scope

In order to design the typical, two-story home in each climate zone, the IECC code for each climate zone, foundation type, heating system, and location were determined based on the criteria presented in this study. The main focus of this study was on the roof and assessing the results based on changing the roof color. The EnergyPlus software was used to model the energy consumption for the IECC building models in this study. The energy savings, net present value (NPV) results, simple payback period (SPP) results, and the environmental impact were assessed from the energy consumption results.

1.5 Assumptions

The following assumptions were made in this study:

1. The electricity and natural gas consumption outputs from the EnergyPlus simulation software reflect the actual energy consumption of the most common residential buildings in each climate zone location.
2. The costs used in this study from the Building Component Cost Community Database (BC3) database accurately reflect the material and labor costs needed to implement a cool and medium roof.
3. The typical meteorological year (TMY3) weather files provided for the EnergyPlus software are accurate representations of the locations in this study.
4. The most common residential building simulation models used in this study have been verified and validated correctly by the Pacific Northwest National Laboratory (PNNL).

1.6 Limitations

The limitations associated with this study are:

1. The accuracy of the results are limited by the accuracy of the simulations performed in the EnergyPlus software and its comparison to the base model.
2. This study does not have a real-life model with measurements to compare to the simulated model in the respective climate zones.
3. The historical perspective for the traditional coating addressed in this study is limited to the past 40 years.

4. The simulations are only focused on the impact of the building envelope based on the changes made by the roof.
5. The typical single, detached, steep-sloped, residential building in the U.S. is used as the only building in this study.
6. The albedo degradation of a cool roof has not been analyzed in this study, in both the one-year and multiple-year analyses.

1.7 Delimitations

The delimitations of this study include:

1. The building simulation models for the most common type of residential housing in the U.S. are considered for this study.
2. Only the simulation representations of single detached residential buildings are used in this study.
3. The other parameters in the house remain unchanged, so that there is commonality throughout the tests.
4. The study is only focused on the U.S.
5. The study only uses the absorption values for a cool roof, medium roof, and a dark roof.
6. The simulation models are only designed to the building standards outlined in the International Energy Conservation Code (IECC).
7. The selected cities and the selected simulation models are used to determine the viability of a cool roof and a medium roof in each U.S. climate zone.

1.8 Key terms

Albedo - The ratio of total reflected electromagnetic radiation to incident electromagnetic radiation.

Absorptivity – The fraction of thermal radiation that the material has absorbed.

Cool roof – A roof that has an absorptance value less than 0.475.

Dark roof – A roof that has an absorptance value more than 0.7.

Emissivity – Ratio of emitted surface radiation to the emitted radiation of a black body at the same temperature.

Material cost – The cost needed for the necessary materials in this study.

Material and labor cost – The cost needed for the labor and material in this study.

Medium roof – A roof that has an absorptance value between 0.475 and 0.7.

Net present value – Used to determine whether the investment is worthwhile for the consumer.

Passenger car – Equivalent to 4,800 kg of CO_2 emissions.

Premium cost – The additional cost applied to cool roofs over other roof colors.

Reflectivity – The fraction of thermal radiation that the material has reflected.

Residential home – Single detached, steep-sloped, residential building in the U.S.

R-value – Resistance to heat flow.

Simple payback period – The minimum time period required to recover the initial investment.

Solar absorptance – The absorptance of the material.

Thermal absorptance – The emissivity of the material.

Thermal conductivity – The time rate of heat flow through a unit area and unit thickness of a homogenous material under steady conditions when a unit temperature gradient is maintained in the direction perpendicular to the area.

Typical meteorological year – An assessment of the typical conditions of a location and recorded solar radiation and other weather conditions at an hourly rate over a one-year period.

U-factor – How well a material conducts heat.

Visible absorptance – The absorptance of the material.

CHAPTER 2. LITERATURE REVIEW

2.1 Basic building heat transfer

As shown in Figure 2.1, heat transfer in a building is from three forms: radiation, conduction, and convection. Convection causes the circulation of warm air to rise throughout the building. As a result, heat loss occurs through the ceiling and the roof when the outside temperature is less than the inside temperature. Radiation primarily occurs due to the radiated heat from the sun. This provides a source of external heat to the building envelope and increases the internal temperature. Conduction occurs when heat from a warmer zone transfers through a solid object, such as a wall, to a cooler zone or vice versa.

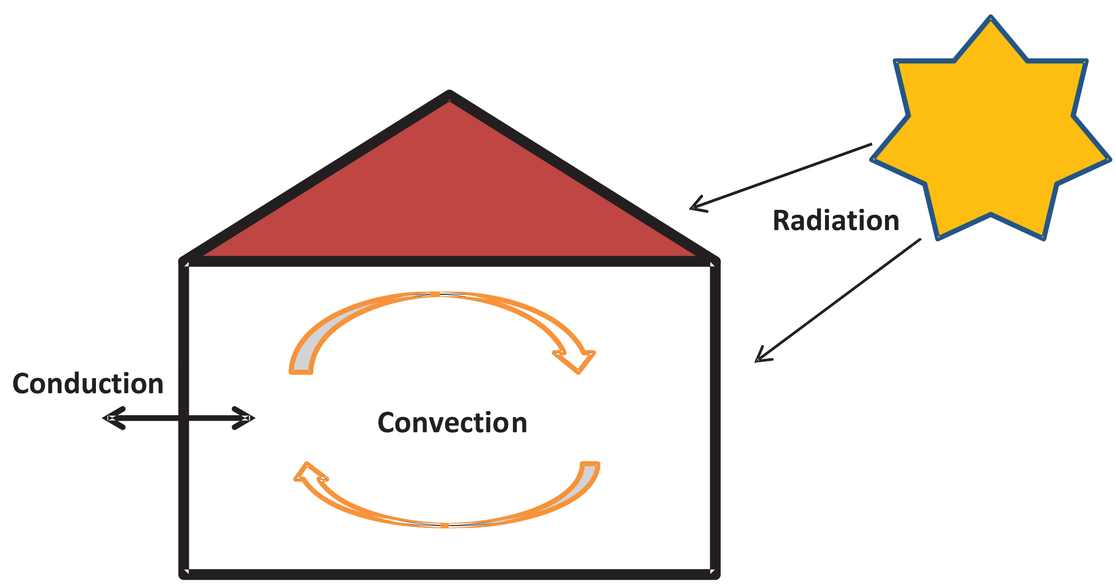


Figure 2.1 Radiation, conduction, and convection heat transfer

In this study, the primary focus is on the heat transfer of the roof. The roof contains the largest amount of service area in a home. The roof also has an influence on the home's interior because of the exposure to the sun. Roof insulation also reduces the amount of rate of heat transfer into the home, a light-colored roof reduces the amount of absorbed heat, and a dark-colored roof increases the amount of absorbed heat.
Thus, the chosen roof color can have an effect on the air-conditioning and heating costs throughout the year (Sustainable Housing Guide, 2014).

2.2 Building energy consumption in the U.S.

The EIA reports that buildings in the U.S. are responsible for 40% of the country's CO_2 emissions. Furthermore, U.S. buildings produce 8% of the world's CO_2 emissions (EIA, 2010). One of the leading factors for the excess amount of greenhouse gases has been the continuous increase of housing construction in the U.S. As provided by the U.S. Census Bureau, Figure 2.2 demonstrates a continuous increase in U.S. housing since 1980. The graph presents a 40% increase in households. Furthermore, the U.S. population has increased over 30% over the same time period (EIA, 2010).

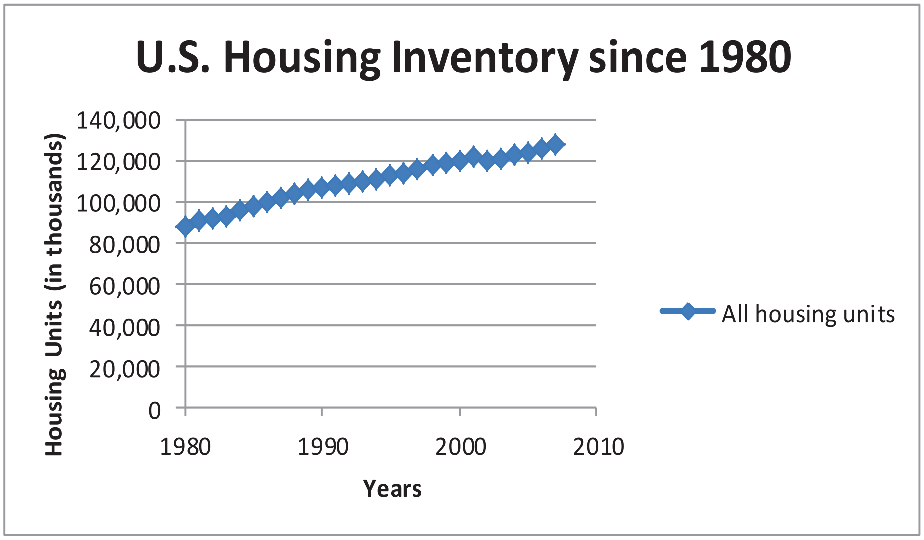


Figure 2.2 U.S. housing inventory since 1980 (U.S. Census Bureau, 2013)

Figure 2.3 illustrates the average square feet of U.S. residential housing, according to the U.S. Census Bureau. As shown, the household size has steadily increased over the past 30 years. In fact, the current household size is 37.9% larger than the average household size in 1980.

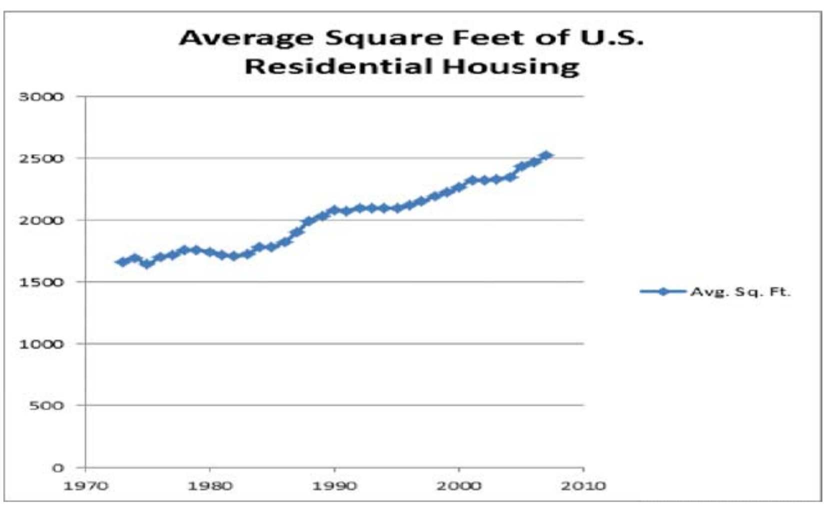


Figure 2.3 Average square feet (sq. ft.) of U.S. residential housing (U.S. Census Bureau, 2013)

Another factor has also been an increase in the use of electricity by U.S. buildings. Since 70% of U.S. energy comes from fossil fuels, this is why CO_2 emissions have continued to increase despite efforts to provide cleaner energy technologies (EERE, 2008).

2.3 Residential building energy consumption in the U.S.

As provided by the 2009 EIA residential energy consumption survey (RECS), Figure 2.4 illustrates the U.S. residential electrical consumption by use. In 2009, 11,320 kilowatt-hours (kWh) was the average amount of electricity consumption for a U.S. household.

Space heating was still the largest energy use by residential users as of the 2009 RECS edition. However, usage for appliances, electronics, and lighting continues to increase with each new EIA publication. The 2005 RECS reported space heating at 40.5%, and appliances, electronics, and lighting were listed at 25.97% (EIA, 2005), representing almost a 10% increase within four years.

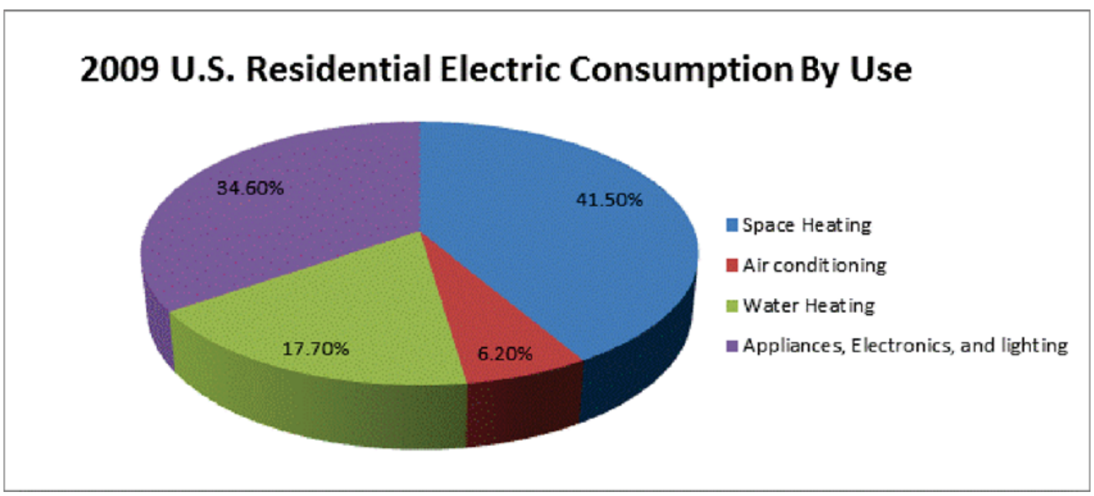


Figure 2.4 U.S. residential electricity consumption by use (EIA, 2009)

Figure 2.5 illustrates U.S. residential natural gas consumption by use, as provided by the 2009 EIA residential energy consumption survey (RECS). In contrast to electricity consumption, natural gas consumption primarily stemmed from two sources: space heating and water heating. In fact, 67% of the reported natural gas consumption was from space heating. Therefore, energy reduction strategies aimed at reducing natural gas consumption would be more effective by focusing on the reduction of energy consumed by space heaters.

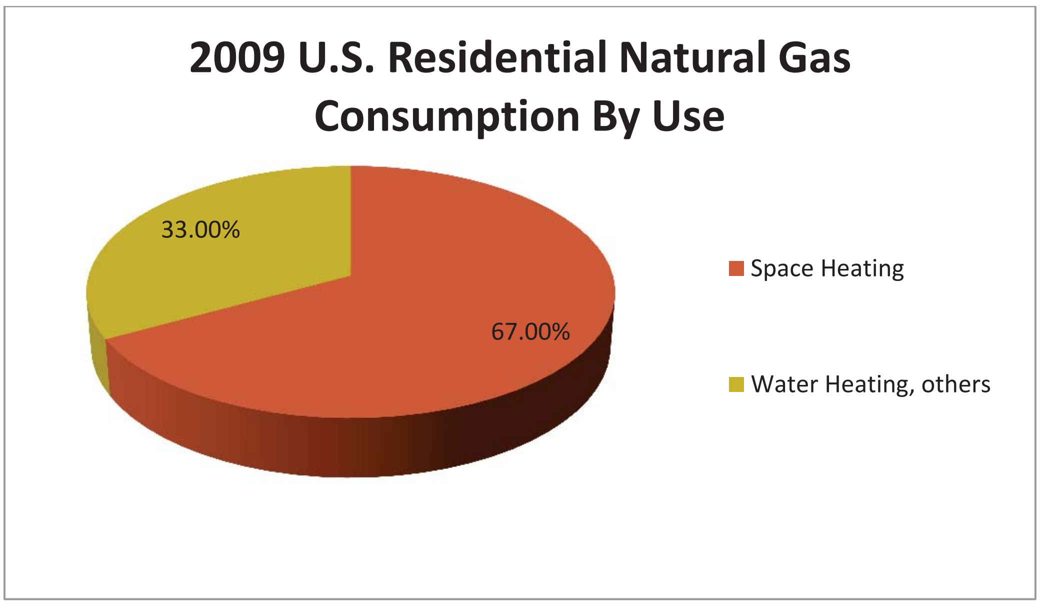


Figure 2.5 U.S. residential natural gas consumption by Use (EIA, 2009)

2.4 Development of the International Energy Conservation Code (IECC)

The modern residential building code was established in 1975 with the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90-75. Then, the Model Energy Code (MEC) was established in 1983 and remained the standard until 1994.

In 1994, the International Code Council (ICC) began to establish one set of construction codes. The ICC is an association that develops international codes that promote safety, cost, and other factors for structures. All 50 U.S. states have adopted their international codes in some context (International Code Council, 2014).

The International Energy Conservation Code (IECC) was developed by the ICC to set the minimum requirements for lighting, appliances, building envelopes, and other energy uses (Responsible Energy Code Alliance, 2013).

Therefore, when the code is applied, buildings must meet or exceed the requirement of the standard. The standard covers all types of residential buildings and was intended to make these buildings become more energy efficient. The International Residential Code (IRC) was another code developed by the ICC for residential buildings. However, this code was not used in this project because the requirements are not as stringent as the IECC and its code guidelines when creating building simulations (International Code Council, 2014).

Initially, the DOE reduced the energy use by 14 % in the building code from the 1975 code to the 2006 IECC. However, the present goal is to reduce energy use based on the 2006 IECC by 30% within the 2012 IECC building code. Furthermore, the 2009

IECC guideline reduced the 2006 IECC by 15%, or halfway toward the goal for the 2012 IECC (EERE, 2010).

2.4.1 Adoption of the IECC standard

The IECC is a well-established residential building standard in the U.S., and different levels of the standard have been established throughout the country.

Figure 2.6 exhibits all current residential building code policies in place throughout the country. The most commonly accepted standard is the IECC 2009 standard, but there are at least 10 states that have either accepted the IECC 2003 standard or that have not yet established a statewide code. Therefore, there is room for improvement in the residential building code in the U.S.

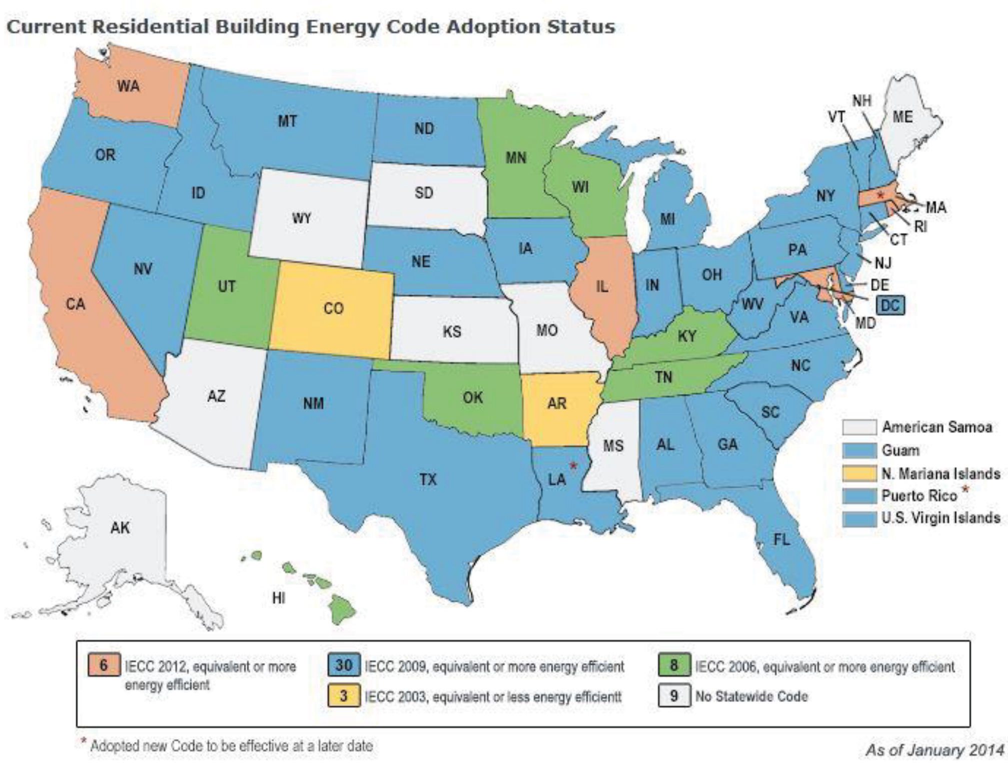


Figure 2.6 Current IECC state policies (DOE, 2014)

Figure 2.7 demonstrates the projected residential building policies for the U.S. by the year 2015. Thirty-nine states are projected to have adopted at least the IECC 2009 standard in their building code by the year 2015.

Researchers at the Pacific Northwest national laboratory (PNNL), with the collaboration of other organizations such as Building Science Corporation, developed the IECC climate zone map. The purpose was to create a simplified map for future building code development.

The 2004 versions of the ASHRAE 90.1 and IECC building codes first included this PNNL climate map. The IECC map depicts 24 possible combinations due to three moisture designations (A, B, and C) and eight climate zones in the U.S.

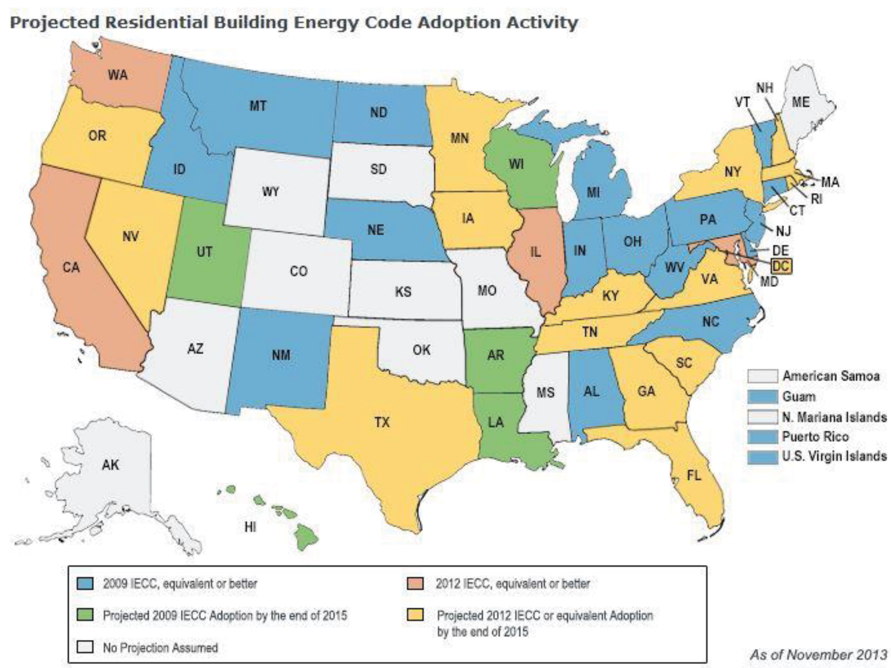


Figure 2.7 Projected IECC state policies (DOE, 2014)

The climate map and its climate designations are used by the IECC and ASHRAE (Baechler et al., 2013). Figure 2.8 displays the IECC climate zone map, as described in the 2009 IECC standard.

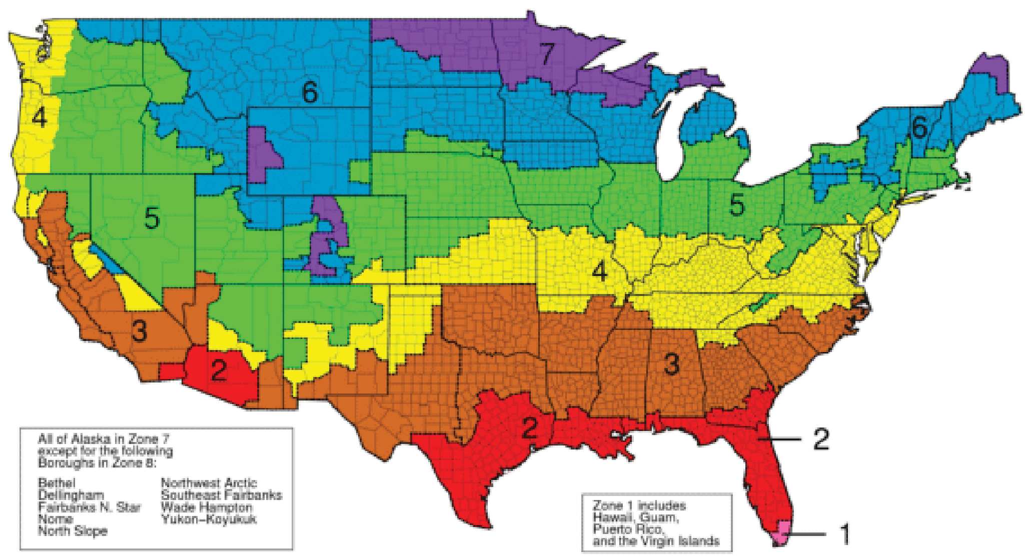


Figure 2.8 2009 IECC climate zones map (IECC, 2014)

2.5 Roof color studies

2.5.1 Definitions of cool and green roofs

A cool roof is a surface that has a high solar reflectivity and a high thermal emissivity. According to the California Title 24 policy, a cool roof requires a minimum of 70% solar reflectivity and a minimum of 75% thermal emissivity (EERE, 2008).

According to the Environmental Protection Agency (EPA), a green roof is a rooftop with a vegetative layer. The EPA further reports that the purpose is to reduce the roof surface temperature and the heat in the surrounding area (EPA, 2013).

2.5.2 Albedo degradation of cool roofs

There have been studies that show albedo degradation of cool roofs as a potential detriment. An experiment analyzing albedo degradation and overall performance of albedo as a roof coating was conducted by Bretz on buildings in California. Four factors of roof coating degradation were considered: insolation, moisture, temperature, and pollutants. The results showed that degradation could reduce the cooling savings potential by 20% after the first year if the roof was not maintained properly.

Therefore, the reflectivity of the cool roof can be affected by external influences. In another study, Cheng et al. investigated the effects of cool roof pigment deterioration in seven distinct locations in California with various types of roof materials. The chemicals chromium, carbon, and iron had the largest impact of the reflective material. The study further suggests that dirt particles and water residue were other factors that caused quicker deterioration of the solar reflectivity of roofs (Cheng et al., 2012).

Similarly, Ichinose et al. examined the long-term effects of external contaminants on test panels that were coated with a reflective coating. Two locations in Tokyo, Japan were used for the study and the focus was to compare highly reflective and conventional paint under a series of tests. The results suggested that precipitation and radiation did have an effect on the paint performance and that a highly reflective PC coating fared better than a conventional coating (Ichinose et al., 2009).

Based on the previous results, the performance and longevity of a cool roof may differ in different types of climates.

2.5.3 Cool roof studies

This section includes studies that highlighted the benefits and detriments of cool roofs. In Nevada, U.S., Akbari used two AT&T concrete buildings and performed a comparison analysis of the solar reflection between dark roofs and cool roofs, and the resultant energy savings. The study reported the annual energy savings of cool roofs to be 100–125 kWh. To summarize, the cost of painting the roof white was deferred to the factory due to the painting being included in the cost for the roof. Assuming that the cost of electricity was $0.1/kWh, the annual energy savings of cool roofs from this experiment was only $10–12.5/year (Akbari, 2003).

Konopacki et al. analyzed the effects of cool roofs in California. The cost of the coatings was paid for by the facility itself, and the coatings were applied by roofing contractors instead of by project personnel. The researcher expressed difficulty citing the cost-effectiveness of the cool roof. Therefore, although there were potential energy savings (between \$0.02/ $ft^2$and \$0.05/ ft^2), the author did not see cool roofs as a cost-effective choice. The researcher further elaborated that the payback period would be long, and the energy savings would not be high enough to be attractive to a facility manager in the area (Konopacki et al., 1998).

In another study, Akbari et al. investigated three different types of buildings in different climate zones in California. One of the purposes of the study was to generate the estimated energy savings from adding a cool roof to these buildings. The study reported that, at its peak, the air-conditioning energy savings reached 52% with a cool roof when compared to a building with a dark roof (Akbari et al., 2005).

The studies by Akbari and Konopacki demonstrated a cool roof to not have a significant impact on the building’s energy performance in Nevada and California. In contrast, the following study by the same researcher highlighted the cool roof to have a significant impact on a building’s performance in California.

Also, the first study discussed the insulation having a potential impact on the results. A research study by Desjarlais et al. regarding the effect of the building envelope suggested that the thermal insulation was more important regarding the effect of the building envelope than thermal surface properties such as the roof albedo. Furthermore, they reported that cool roofs were a detriment to the energy efficiency of buildings during the heating season. However, in the study, only the summertime conditions were observed in the analysis between cool roofs and dark roofs. The study reported that a dark roof in California would require as much as R-52 insulation in order to replicate the results for a cool roof with an R-19 insulation in California (Desjarlais et al., 2007). In a climate such as in Arizona, a study by Jo et al. demonstrated that cool roofs and insulation improvements reduced the annual energy consumption by at least 8.7% when compared to the base model (Jo et al., 2010).

Few of the studies focused on determining the impact of cool roofs in a cold climate location. A study by Saber et al., based on the moisture measurements and the potential heat gain, predicted that the locations of Toronto, Montreal, Seattle, Wilmington, and Phoenix could benefit from the implementation of cool roofs. They reported that black roofs had heat gains as high as 6.8 times higher than white roofs (Saber et al., 2012).

The above study demonstrated the potential of cool roofs in cold climates. An international study was needed to determine if there was potential for cool roofs throughout the world. Synnefa et al. investigated the effect of cool roofs by obtaining data for the various climatic conditions from the METEONORM database. Simulations were performed with a simple one-story home and applied to the climatic conditions of 27 cities throughout the world.

The first test utilized the roof's solar reflectivity, heating and cooling loads of the building, and thermal comfort temperatures. It was concluded that the locations that benefitted the most from a highly reflective solar roof were in hot climates. Also, the researcher concluded that cool roofs improve indoor thermal comfort. Another finding was that the U-value of the roof had a significant effect on the energy savings for the building. Finally, the study reported that, with an increase of roof reflectivity from 0.35 to 0.75, the energy savings varied between 10.7% and 27% (Synnefa et al., 2007).

Kolokotsa et al. reported the effect of a cool roof coating on a building in Greece. The researchers in this study performed a comparison analysis of the effects of cool roof coating, roof insulation, and improved windows. The results showed that a cool roof would reduce the cooling load by 27% but increased the heating load by 43%. In the study, the heating load was only a small portion of the total energy consumption. As a result, the cool roof reported energy savings of as much as 19% (Kolokotsa et al. 2012).

Levinson et al. observed the effect of non-white, near-infrared reflective coatings for roofs in California. The experiments in this study suggested that the cool coatings are viable with a payback period of five to seven years, considering just the cost premium of cool roofs. Furthermore, the study reported that the cool roof reduced the peak ceiling heat flux by as much as 21% (Levinson et al., 2007).

Applying the results to the state of California, the data suggested that the implementation of cool roofs would remove 35 kton of CO_2 emissions, or the EPA CO_2 equivalent of removing 6,615 passenger vehicles from the road (EPA, 2014).

Suehrcke et al. investigated the effect of roof color on the downward heat flow within the roof. The results suggested that the light roof color reduced the heat transfer into the building by as much as 30% in comparison to a dark roof color. The researcher reported that this article only analyzed buildings in climates without a heating load. Therefore, future research could investigate the effect of both heating and cooling loads in a building (Suehrcke et al., 2008).

Parker et al. documented the effects of cool roof coatings in nine different sites with different building parameters in Florida. The experiments were used to observe the estimated energy savings for the cooling load during the cooling season. One of the problems that Parker discovered was that the summer cooling energy savings may be offset by the winter season heating needs for the building. Therefore, the researcher suggested that climate has an influence on the potential savings or losses for cool roof coatings. Therefore, further research was suggested for climate-related heating interactions (Parker et al., 1997).

Shen et al. conducted experiments to evaluate the effect of three different types of coatings on the heating and cooling loads on identical buildings in Shanghai, China. Furthermore, the researchers observed the electrical consumption, heat gains, and building surface temperature outputs of these buildings. The results suggested that the roof had a negative effect on the building in Shanghai when the heating and cooling loads were taken into account together (Shen et al., 2011).

Reagan et al. (1979) found that cool roofs did benefit the building envelope, but the impact was small because the roof only affected about 20% of the total building envelope. The researcher performed an analysis of different colors consisting of light, medium, and dark. The researchers further discovered that adding insulation would be more effective at reducing summer heat gain and winter loss than changing surface color (Reagan et al., 1979).

In another study, the roof of a retail building and storage facility was coated with a reflective coating. The results suggested that the coating did not have a significant effect on the air-conditioning energy use, but did improve thermal comfort (Akbari et al., 2005).

Akbari et al. conducted a DOE-2 simulation of cities throughout the U.S. with cool roofs. As the climate got cooler, the energy savings decreased for the cool roof. Phoenix exhibited the highest annual energy savings of $51, and annual energy savings in Miami were $31 (Akbari et al., 1999).

2.5.4 Social impacts of cool roofs

The EPA (2012) reported that applying cool roof coatings to steep-sloped roofs was not a recommended option because moisture problems and water damage could occur on the shingle foundation (EPA, 2012).

Bretz et al. determined that two potential concerns for cool roofs with steep-sloped residential buildings were aesthetics and the lack of variety. Therefore, the aesthetics of the building may become blander and introduce glare into the environment, and visual discomfort and other social issues may occur if applied on a large scale.

Finally, the article reported that architects loved being in control of the colors for the building, so a generic cool roof may present issues for architects, designers, and owners due to the lack of flexibility in color selection (Bretz et al., 1997).

Uemoto et al. (2010) reported that cool paints are not significantly different than conventional paints. Although they initially cost more, the researcher suggested "cool paints can improve thermal comfort conditions of low-cost housing, industrial buildings, and farm buildings constructed with fiber cement roofing sheets." Furthermore, a recommendation was suggested to assess the effects of cool paints on air-conditioned buildings (Uemoto, 2010).

2.5.5 Green roof

A key component that has been overlooked in many research articles on cool roofs was the aspect of a neutral, or medium, color to compare against the dark and the cool color coatings. However, in a research report of cool roof technology in London, the optimal value of reflectivity in London was reported to be 0.6 (Kolokotroni et al., 2011).

Castleton et al. investigated the costs and benefits of green roofs and the value of applying them as an external layer to existing buildings in the United Kingdom. The article discussed the difference between wet soil and dry soil for green roofs and the impact on the effectiveness of the system. The ratio of total reflected electromagnetic radiation to incident electromagnetic radiation was defined as albedo. The article discussed the effect on indoor temperature based on the direction of the roof orientation, the types of roofing materials used, and the selected roof surface color in warm climates. The results suggested that the green roof to have annual energy savings of 2% for a well-insulated home and, as much as, 44% for an un-insulated home (Castleton et al., 2010). A study by Kolokotsa et al. found green roofs to be more efficient than cool roofs (31% to 17%), but the researchers suggest an in-depth cost analysis was needed to determine which measure was more effective (Kolokotsa et al., 2012).

Scherba et al. developed experiments and simulations to analyze the impact of a traditional roof and a PV roof on the urban heat island effect. The results were observed in six U.S. cities, and the three types of roof color were black, white, and a green vegetation roof. The time frame for the analysis was from June 1 through August 31, which was designated as the cooling season. The results showed that by changing the color from black to white, the total heat flux decreased by 80%, and it decreased by 52% when it was changed from a black rooftop to a green vegetation roof. EnergyPlus was the simulation program used in this analysis. The EnergyPlus input data files (IDF) used in the simulations were for DOE commercial buildings based on ANSI/ASHRAE/IESNA Standard 90.1-2004. Finally, the material properties used in the material database were developed by the Lawrence Berkeley National Laboratory. Furthermore, the researcher discussed the effects of degradation on white roofs and used a reflective value of 0.7 instead of 0.8 or greater in simulation analysis of cool roof buildings (Scherba et al., 2011).

2.5.6 Emerging studies for roof color

Some emerging studies for roof color were focused on a color changing roof color and different applications of color change in a building. A study by Bange investigated the use of tungsten oxide thin films for electrochromism, thermochromism, photochromism, and other applications. The two main types of changes for thermochromism were phase change and a gradual change based on the temperature (Bange, 1999).

A study by Ye et al. conducted experiments using Poly(N-isopropylacrylamide) (PNIPAM) material to analyze its effects on thermochromic applications. The focus was on the material's longevity because thermochromic applications typically last for only a few days. PNIPAM was used in the thermochromic system to turn the material black to absorb sunlight when the temperature was cold and turn the material transparent when the temperature was warm. The results suggested that this material operated as predicted for the varying temperatures and that it could be used in building applications (Ye et al., 2012).

A study by Joudi et al. conducted measurements and simulations of reflective coatings on cabins in Sweden. One of the tests consisted of analyzing the effects of applying reflective coatings inside and outside of the cabin. The results suggested that a reflective coating on the interior benefited a cold climate, a reflective coating on the exterior benefited a warm climate, and the combination of both benefited a mild climate. Furthermore, the researcher reported that the inner and outer coatings depended on the internal heat load, ventilation rate, and climate. The results reported that the energy savings for the interior reflective surfaces were 2% when compared to dark surfaces (Joudi et al., 2013).

2.6 Cool roof policies

According to the ASHRAE Standard 90.1-2010, a cool roof is required in climate zones 1–3. Furthermore, a cool roof was defined as having a minimum solar reflective index (SRI) of 64 or a combination of a minimum solar reflectivity of 0.55 and a minimum thermal emittance of 0.75.

There have been policies set in place in the United States that have required for cool and green roofs to be implemented. The Global Cool Cities Alliance (GCCA) desired to reduce climate change and costs by implementing strategies to promote reflective materials to be implemented into buildings. Some of the cities that helped co-found the alliance were from cold climates, including New York and Chicago (Global Cool Cities Alliance, 2011).

The DOE suggests that state energy offices could develop energy efficiency programs with incentives to encourage residents to support the program while also getting rewarded financially. Furthermore, utilities could provide programs and incentives to encourage peak-load reductions for their locations (2008).

Policy acts such as the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 have directed the DOE to set new appliance efficiency standards in accordance with the laws. Therefore, since 2006, new appliance standards have steadily changed, partly due to the policy acts (EIA, 2010).

A policy in Philadelphia requires a green roof or a reflective roof on new construction of commercial and low-slope residential buildings. Tax incentives allow companies to earn between \$0.60 and \$1.80/ft^2, which helps cover some of the costs for the material and labor (RCI-Online, 2010).

In 1995, Georgia became the first state to add cool roofs to its energy code, which required a minimal thermal emittance of 75% and solar reflectivity of 75% for cool roofs in the state (EERE, 2008).

Florida used a similar approach to Georgia, lowering the amount of required insulation depending on the solar reflectivity of the roof. Therefore, the state required a minimum of 70% solar reflectivity and 75 % thermal emittance in exchange for a reduction of insulation in the building (EERE, 2008).

The DOE reported that Chicago added to its energy code requirements in January 2003 to require reflective roofs on all buildings with low-sloped roofs. However, exceptions were made for buildings that had no heating or cooling system and that had relatively small energy peaks.

California developed its energy code called Title 24 in 2001, and cool roofs were incorporated as an option. Similar to Florida's cool roof definition, a minimum of 70% solar reflectivity and a minimum of 75% thermal emittance were required to satisfy the cool roof requirement. In 2005, the state made the cool roof application a mandatory addition for all new construction and projects on roofs greater than 2,000 ft^2, or 190 m^2. Since 2006, California has investigated whether cool roofs could be applied to steep-sloped residential homes as well and has established cool roof requirements for homeowners (EERE, 2008).

2.7 Building energy simulation programs

A building energy simulation program is a tool that can be used to simulate a building and determine the influence of changes on a building in a test environment. Therefore, the purpose and accuracy of the simulation program is important to note for proper use and documentation of the simulation results.

A study by Zhu compared a building that meets the minimum requirements and another that incorporates innovative building technology in Las Vegas. The two simulation software packages used in this analysis were eQUEST and Energy 10. The results revealed that the eQUEST software performed better than the Energy 10 software for the experiment due to its accuracy in simulating the water-cooled condensers (Zhu, 2009).

Romeo et al. developed experiments on a cool roof on a school in Trapani, Italy. The measured results suggested that the cool roof application performed better than the existing application for the school during the cooling season. In the TRNSYS simulation program, the building was analyzed, and the roof reflectivity and insulation level were adjusted and analyzed with a cooling system set at 26°C. High levels of insulation helped offset the losses for cool roofs at low temperatures. One concern that the researcher outlined was that "insulation levels need to be accurately determined in climatic conditions characterized by mixed heating and cooling uses." In addition, the researcher suggested that a moderate amount of insulation in combination with cool materials fared better for southern European countries than too much insulation (Romeo et al., 2011).

Gentle et al. conducted an experiment utilizing the EnergyPlus software and analyzed a building in Australia. Simple cost benefit and various costs, such as for insulation, were implemented to quantify the data results from the EnergyPlus software. A high solar albedo exhibited great energy savings for the building and, when combined with a low R-value, demonstrated the optimal energy savings for the experiment (Gentle et al., 2011).

2.7.1 EnergyPlus

The EnergyPlus software was developed by the DOE. It has the ability to do environmental impact calculations, generate heat transfer and control models, measure localized weather data, solve analytical problems in time steps of under an hour, and examine the effects of building materials on the building envelope.

The Input Data File (IDF) describes all aspects of an EnergyPlus simulated building, which includes building geometry, construction materials, glazing characteristics, internal loads, mechanical equipment, heating, ventilation, air-conditioning (HVAC) operations, and human occupancy schedules.

2.7.2 EnergyPlus benchmark models

Another important element to using any simulation program is the need of a reference, or benchmark, model. The DOE has developed a database of IECC-based residential models created in the EnergyPlus software. The models are based on the 2006, 2009, and 2012 IECC standards. Furthermore, the models are divided based on the HVAC equipment and weather location used for the model. The DOE website reports that there are 11,421 different single-family and multi-family models available for use in the EnergyPlus database (U.S. BECP, 2013).

A research study by Peng at MIT conducted a life cycle assessment of benchmark residential buildings in the U.S. He determined that benchmark models in the experiment were homes created in the EnergyPlus software based on the procedures outlined in the Building America House Simulation Protocol (BAHSP) (Peng, 2011).

Researchers have found that using a benchmark model is not a deterrent at all. In fact, it can be a benefit for the research community. Fumo et al. performed a study to estimate the annual energy consumption in benchmark buildings using the EnergyPlus software. The researcher suggested that the establishment of a benchmark model alleviates the burden of having to learn the software thoroughly before creating a model. Also, buildings that are similar to the reference building model, presumably, are supposed to generate similar energy consumption patterns to the reference building model. The statistical analysis used to create the reference models was thorough and provided good samples of the entire building stock and specific locations. Finally, these models were developed to provide consistent baseline comparison (Fumo et al., 2010).

In another study, Field et al. (2010) reported that the reference buildings are good tools for regional and national simulation studies because the buildings' thermal envelopes vary depending on the climate. For example, a specific energy design change may be implemented across several climate zones or even across building types in one climate zone (Field et al., 2010).

However, large-scale projects can still be very time-consuming, even with the use of reference buildings. Therefore, Hopkins et al. (2011) developed a tool that attempted to generate nationwide simulations of benchmark single-family homes. The tool generated simulation outputs for the single-family homes that were comparable to the data provided in RECS. The tool not only is of interest in simulating large numbers of single-family homes but is of potential interest to politicians as well (Hopkins et al., 2011).

Therefore, the researcher encouraged readers to utilize the reference buildings in hopes of avoiding unnecessary duplication with building energy simulations. Finally, PNNL used the reference buildings to demonstrate to the ASHRAE 90.1 standard committee that the reference models were sufficient and progress was being made towards the 30% improvement from 90.1-2004 to 90.1-2010 (Field et al., 2010).

2.7.3 Verification and validation process of simulation models

2.7.3.1 History and significance

Measurements for real-world applications and simulation models can be subject to uncertainty without a verification process. In fact, inconsistencies with a variety of measurement and verification protocols in the 1990s caused much uncertainty for energy efficiency projects (Efficiency Valuation Organization, 2014).

Therefore, professionals from both the DOE and the Lawrence Berkeley National Laboratory initiated the process to develop an international energy efficiency savings measurement and validation protocol in 1994. Initially, the efforts were focused on assisting energy professionals in the U.S., Canada and Mexico. Over time, hundreds of energy professionals became involved from around the world.

In 1996, the North American Energy Measurement and Verification Protocol A (NEMVP) was established as a framework for standard industry practice. The international aspect of the NEMVP protocol was reflected in 1997 with the development of the International Performance Measurement and Verification Protocol (IPMVP). Dozens of countries were involved in the process to ensure that the protocol reflected the industry standard practice internationally (IPMVP, 2014).

Option D in the IPMVP reflected industry standards regarding energy simulation tools and the resulting energy savings and verification process (Efficiency Valuation Organization, 2014).

Because of the immense participation of the industry internationally and the protocol’s flexibility, the protocol has been accepted as a national standard for measurement and verification in the U.S. and has garnered acceptance as a protocol internationally (IPMVP, 2014).

The IPMVP has been incorporated in many U.S. states as part of energy efficiency programs for various types of customers. The protocol has helped cut costs, garner wider acceptance of energy efficiency reports, and become the basis for determining energy savings in the U.S. In fact, some states, such as California, New York, and Texas, have the protocol established in their state energy efficiency program. More recently, the U.S. Green Building Council has sought to integrate the protocol for the Leadership in Energy and Environmental Design (LEED) rating (IPMVP, 2014).

2.7.3.2 Option D: verification of energy simulation programs

Option D outlined four major points to consider when using this for the verification of energy models in energy simulation programs (IPMVP, 2014).

1) Trained and experienced personnel with the software must conduct the simulation analysis.
2) Input data should be based on the best available information.
3) Models must be "calibrated" to ensure that the energy outputs match the real-world application of the model. Weather data is necessary for this process.
4) The process needs to be documented, as well as the software used (and the version), so that future research can be performed to review the provided information.

2.7.3.3 Minimum energy standards

The IPMVP reported that the minimum building energy standard may be utilized as the baseline model for the energy savings analysis. However, in order for the savings to be reported, a building needs to perform equal to or less than the model with the minimum energy standard (IPMVP, 2014).

2.8 Literature Review Summary

Previous studies reveal that there are benefits to using a cool roof in warm climates. However, recent policy changes suggest that cool roofs can also be beneficial in colder climates. Therefore, this study will assess the impact of a cool roof and a medium roof in various types of climate zones. Furthermore, previous studies have arbitrarily chosen the heating and cooling seasons without reference to a standard or even the chosen methodology. This study will demonstrate the method used to determine the heating and cooling season in each climate zone and determine if it has an impact on the effectiveness of the cool roof and the medium roof.

The literature review also presented that the environmental impact is typically assumed to be beneficial but not necessarily assessed. Therefore, the CO_2 emissions within the energy analysis will be analyzed in this study to determine whether a cool roof and a medium roof have a positive or negative impact on the environment.

Finally, previous simulation studies do not demonstrate a verification process for the simulation models. In fact, one study admits that it arbitrarily picked the model and it should be re-assessed with a more verified model in the future (Synnefa et al., 2007).

Therefore, this study includes an international verification process for simulation models and bases the simulation models on a verified residential building code (IECC) to ensure that the results presented are valid and verified.

Previous studies of cool roofs typically assess this type of roof only against the dark roof. Therefore, this study will include a neutral roof color to determine if this type of color will perform better than both the dark and the cool roof in certain climate zones.

CHAPTER 3. RESEARCH FRAMEWORK AND METHODOLOGY

The purpose of this study was to analyze the economic, environmental, and energy impacts of cool and medium roofs with residential building models in different climate zones in the U.S. The EnergyPlus building energy simulation program was used to output the electricity and natural gas consumption for the cool and medium roofs on buildings in each U.S. climate zone. The environmental and economic analyses were then performed to determine whether cool and medium roofs were viable options in the respective climate zone in the U.S. The framework and methodology in this study are outlined in this chapter.

3.1 Research framework

3.1.1 Building energy software

EnergyPlus Version 8.0.0 is the building energy software used in this study. It is freely available on the DOE website for public use and is widely respected in the industry. The software is used to create building models and obtain energy outputs for economic and environmental analyses. All simulations were run on Windows 7 on a 64-bit, 2.8GHz, Intel dual core processor, and the simulation times ranged from 1–10 minutes depending on the building model.

The following examples are discussed in Chapter 2.7 that uses the EnergyPlus software (Gentle et al., 2011; Field et al., 2010; Akbari et al., 1999; Peng, 2011; Fumo et al., 2010).

3.1.2 Test plan for building energy simulation program

Figure 3.1 summarizes the test plan overview of the use of EnergyPlus for this project. First, the location and designated IECC building was chosen. Next, the roof color of the building was changed to either a cool or a medium color. Then, the electrical and natural gas energy outputs were observed for the roof color.

Figure 3.1 Roof color test plan

Finally, the results were compared to the reference dark roof through comparison analyses of energy, economics, and the environmental impact, as explained in the subsequent sections.

3.1.3 Economic analysis

The first test was to determine the annual energy savings for each test compared to the baseline model. First, the electricity and natural gas costs were obtained from the energy consumption outputs from the EnergyPlus simulation software for the building models. Then, the annual electricity, natural gas, and energy savings were assessed by comparing the results of the cool and medium roofs to the reference dark roof model.

The second test was to determine the simple payback period (SPP) and the net present value (NPV) for each test when the costs of painting the home are taken into account. The SPP analyzed how long it would take to achieve a return on investment for each climate zone when material and labor costs are taken into account.

The Encyclopedia of Earth documented that roof coating distributors recommend applying a new color coating over a 10-year period (Encyclopedia of Earth, 2008). Therefore, the NPV analyzed the value of this investment over a 10-year period, taking into account the energy savings as well as the initial costs for the implementation of a cool or medium roof.

3.1.4 Environmental analysis

First, the CO_2 emissions for the cool, medium, and dark roofs were obtained. After that, a comparison analysis was conducted to determine the annual CO_2 emissions saved when the home was switched from a dark roof to a cool or medium roof. Then, the CO_2 emissions were calculated for each roof type for a 10-year period to determine how many passenger cars would be removed from the road for each climate zone.

3.2 Methodology

Task 1: Select the climate zone.

Task 2: Select the building that best represents the climate zone.

- Select the building and city location based on the sample size, most common heating system type, and most common foundation type.

Task 3: Verify the selected building model.

- Ensure that the building meets the 2009 IECC building standard.

Task 4: Change the roof color.

- Change the roof color to a cool or a medium color.

Task 5: Simulate the model using the EnergyPlus software.

Task 6: Observe the results.

- Extract the natural gas and electricity consumption outputs for the simulation.

Task 7: Obtain the electricity and natural gas costs based on the calculations from the prices provided by the EIA.

Task 8: Determine the energy savings in comparison to the dark roof.

Task 9: Document the SPP for implementing a cool or a medium roof.

Task 10: Document the NPV for implementing a cool or a medium roof.

Task 11: Determine the environmental impact of the implementation of a cool or a medium roof.

3.3 Building selection

According to Building America, a good reference for the U.S. residential prototype building is the 2009 IECC model, which was based on the 2009 IECC building standard code (Hendron et al., 2010). As noted earlier, thirty-nine states are projected to adopt a building standard policy at least as stringent as a 2009 IECC model for their residential codes by 2015.

3.3.1 Climate zones

Table 3.1 represents the zone number and descriptions for the different international climate zones, according to ASHRAE. As illustrated in Figure 1.1, the IECC climate map is divided into seven different climate zones. With ASHRAE, this chart breaks down each zone further with prefixes, if possible, for each climate zone for humid, dry, and marine.

Table 3.1
Climate zone number and descriptions (ASHRAE, 2008)

Zone Number	Zone Descriptions
1A and 1B	Very Hot-Humid (1A) Dry (1B)
2A and 2B	Hot-Humid (2A) Dry (2B)
3A and 3B	Warm-Humid (3A) Dry (3B)
3C	Warm-Marine (3C)
4A and 4B	Mixed-Humid (4A) Dry (4B)
4C	Mixed-Marine (4C)
5A, 5B, and 5C	Cool-Humid (5A) Dry (5B) Marine (5C)
6A and 6B	Cold-Humid (6A) Dry (6B)
7	Very Cold
8	Subarctic

3.3.2 Climate zone location selection

In this section, the respective location for each climate zone is determined. Each IECC building in the database is based on a sample size of single-family permits collected through the Residential Energy Consumption Survey (RECS) (Taylor et al., 2012). Therefore, the location with the largest sample size was chosen for each climate zone. This was determined because a larger sample size would, in theory, increase the accuracy of the building's representation of the selected location and, in this case, the respective climate zone.

A full breakdown of all of the climate zones, locations, and their sample sizes are located in Appendix A. The suffixes A, B, and C that are attached to the climate zone locations stand for moist, dry, and marine.

3.3.3 Determination of the weather files

The weather files used in this study are based on the typical meteorological year (TMY3). The National Renewable Energy Laboratory (NREL) produced the TMY3 data sets and manual under funding from the DOE's Energy Efficiency and Renewable Energy Office. The NREL reports that the TMY3 dataset assesses the typical conditions of a location and records solar radiation and other weather conditions at an hourly rate over a one-year period. It should be noted that it was designed to be used for building simulations to compare the performance in U.S. locations, energy systems, and building configurations (National Solar Radiation Database, 2008).

3.3.4 Foundation selection

In this section, the foundation and heating system for the IECC buildings are selected. Appendix B contains all of the data for the locations and foundation types for U.S. residential buildings. Table 3.2 is a simplified version that is focused solely on the locations selected in this study. Therefore, the foundation type with the highest percentage for each state was selected to represent the climate zones. As shown below, there are four main foundation types: crawlspace, unheated basement, heated basement, and slab.

For example, in this study, an unheated basement was selected for Pennsylvania in climate zone 5A, a heated basement for Wisconsin in climate zone 6A, and a slab-on-grade foundation for Florida in climate zone 2A. This was essential in selecting the most common residential building for each climate zone.

Table 3.2
Foundation types (% used) (Taylor et al., 2012)

	Foundation Types			
State	Slab	Heated Basement	Unheated Basement	Crawlspace
Pennsylvania	28.9	24.6	32.8	13.7
Wisconsin	14.9	45	29.7	10.4
Minnesota	22.1	46.9	15.5	15.5
Virginia	33.2	24.2	9.8	32.8
Florida	87.7	0	0.4	11.8
Texas	79.6	0.3	0.4	19.8
Colorado	30.7	28.2	9.9	31.2
Wyoming	26.7	36.6	11	25.6
California	59	1.2	4.9	34.9
Washington, Alaska, Hawaii	37	8.9	3.1	51

3.3.5 Heating system selection

In this section, the heating system for the IECC buildings is selected. Table 3.3 displays all of the different census divisions and the percentage of homeowners that used a specific type of heating system.

The heating system was chosen for the building based on the census division for the climate zone. Four different heating systems are examined in the table: natural gas, electric heat pump, electric resistance, and petroleum gas/propane.

Different types of air conditioning systems were not evaluated in this study. The main reason is because 88% of U.S. single-family homes have installed central air-conditioning units. Therefore, electricity is the main source of energy for these homes and, due to its high percentage, it has been assumed to be in every home for the provided typical residential models (Taylor et al., 2012).

Table 3.3
Heating system for census divisions (% used) (Taylor et al., 2012)

Census Division	Electric Heat Pump	Gas Heating	Oil Heating	Electric Furnace
New England	10.8	57	31.1	1.1
Middle Atlantic	24.5	69.2	4.6	1.7
East North Central	22.5	76.2	0.5	0.7
West North Central	39.6	56.7	0.2	3.4
South Atlantic	78.9	19	0.1	2
East South Central	68.9	28.9	0	2.1
West South Central	37.5	48.1	0	14.5
Mountain	19.4	77.8	0.2	2.6
Pacific	34	62.9	0.2	2.9

3.3.6 Roof color selection

As discussed in the literature review, cool roofs have become a major focal point in terms of reducing building energy consumption by adjusting roof coloration. However, few of the studies included a medium color to determine if it would perform better than the cool roof under certain conditions.

According to the EPA, 90% of the roofs in the U.S. are dark colored (Energy Protection Agency, 2012). Therefore, the dark color is the reference color in the economic and environmental analysis. After doing interviews with architects, Bretz et al. suggests that the purpose may be due to the aesthetic appeal of dark roofs and the potential problem of glare with cool roofs (Bretz et al., 1997).

The required absorptance levels for light, medium, and dark colors as reported by the Australian government are demonstrated in Table 3.4. Therefore, the solar absorptance of a light/cool color is 0.2 in this study to demonstrate that the material reflects 80% of the light from the building. The dark color has a solar absorptance of 0.8 to resemble a standard grey roof, which absorbs 80% of the light to the building. The medium color has a solar absorptance of 0.5 since that number is the average of the selected dark color and the selected light color.

Table 3.4
Roof color and solar absorptance (Building Sustainability Index, 2014)

Solar Absorptance	Typical Color
< 0.475	Light
0.475–0.7	Medium
> 0.7	Dark

3.3.7 Building breakdown

The previous sections depict the selection of the climate zones, locations, heating source, and foundation. Table B.3 in Appendix B lists an overall table of the climate zones, selected locations, heating source, and foundation. These items were used to select the correct IECC reference building for each location in this study.

3.4 Verification process

Multiple verifications have been undertaken in this study to ensure that the models used in this study are accurate and reliable.

3.4.1 Verification by minimum building requirements

The IPMVP reported that, if required by law, the baseline model can be set to the minimum energy standards (IPMVP, 2014). Therefore, the models used in this study were created based on the minimum energy requirements as outlined in the 2009 IECC building code. Appendix B breaks down all the requirements met for the building models of each climate zone in this study. Furthermore, Field et.al. reported that the reference building models have undergone a large amount of research and has been verified by numerous sources such as academics, industry professionals, national laboratories, and other users of the EnergyPlus software (Field et al., 2010). Therefore, the models meet minimum energy standards and have been verified and confirmed by professionals in the industry.

3.4.2 Verification based on previous studies

This section focuses on the verification process of the simulation models against results from two previous studies of cool roofs in the literature review.

According to Chapter 2.7.3.2, this is the four-step process that should be followed for verification of building simulation models:

1) Trained and experienced personnel with the software must conduct the simulation analysis.
2) Input data should be based on the best available information.
3) Models must be “calibrated” to ensure that the energy outputs match the real-world application of the model. Weather data is necessary for this process.
4) The process needs to be documented, as well as the software used (and the version), so that future research can be performed to review the provided information.

To ensure consistency, this is how the four-step process was used on the simulation models in this study.

1) Trained and experienced personnel with the software must conduct the simulation analysis.

In previous studies, the researchers determined that the building characteristics for the reference model to be the same as the typical residential building in a designated location. Furthermore, the assumption is that the models have been verified by numerous academic and industry sources and are a true reference for the designated building and location (Field et al., 2010; Akbari et al., 1999; Peng, 2011; Fumo et al., 2010).

2) Input data should be based on the best available information.

The simulation models in this study are based on the 2009 IECC building standard, which is the standard that has been at least partially adopted into residential building code for 39 states (International Code Council, 2014). Therefore, the simulated models were based on the most used residential code in the U.S.

3) Models must be "calibrated" to ensure that the energy outputs match the real-world application of the model. Weather data is necessary for this process.

The simulated models were calibrated with the TMY3 weather files to ensure that the energy outputs match the real world application of the model. These weather files were created by the NREL in collaboration with the U.S. Energy Efficiency & Renewable Energy department (EERE) (National Solar Radiation Database, 2008).

4) The process needs to be documented, as well as the software used (and the version), so that future research can be performed to review the provided information.

This study follows this final step by including documentation throughout this document to ensure that others can use the software and follow the documented process to replicate the results.

Therefore, this demonstrates how the study incorporated the verification process and how the study met the verification requirements.

3.4.2.1 Miami, Florida location

Akbari et al. reported an annual energy savings of $31 when a cool roof was applied to a building in Miami. In the study, Akbari et al. used reference models similar to the ones utilized in this study (Akbari et al., 1999). Therefore, a comparison was performed to determine if this study could replicate the data in a previous study. The purpose is to show that the models from the database not only meet building standards but are also capable of outputting accurate data. This study reported an annual energy savings of $36 for a simulated residential building model in Miami. The Miami model was selected based on the same selection process that was followed for the building models selected in this study. The IPMVP reports that the bias error has to be between ±20% for a comparison based on monthly results. The reported savings was 18.9% different from the savings in the Akbari study. Therefore, it was within the tolerable limits for the protocol.

3.4.2.2 Phoenix, Arizona location

Abkari et al. reported that the simulated reference building in Phoenix, Arizona, exhibited annual energy savings of $51 (Akbari et al., 1999). Similar to the study in Miami, FL, this study selected the building model for Phoenix based on the building selection process outlined in this study. This was also used to compare the results to the previous study to ensure that the building models operate within tolerable limits. This study reported annual energy savings of $50 for the Phoenix residential building model.

Therefore, the reported savings represent a 1.96% difference from the results in the Akbari study, and the mean bias error is within the tolerable limits for the IPMVP protocol.

3.5 Economic analysis

3.5.1 Electricity and natural gas costs

The electricity and natural gas costs used in this study are from the 2012 annual average cost tables provided by the EIA (Energy Information Agency, 2014, 2013).

The electricity calculations were performed by taking into account the amount of electricity consumption in kilowatt-hours (kWh) and multiplying it by the state's designated electricity rate, as shown in Equation 1.

$$Electricity\ (\text{in }\$) = \text{kWh} \times Elec.rate(\frac{\$}{\text{kWh}}) \tag{1}$$

The natural gas, or heating, calculations were performed by taking into account the amount of natural gas consumption in therms multiplied by the state's designated natural gas rate, as shown in Equation 2.

$$Natural\ Gas\ (\text{in }\$) = \text{therms} \times natural\ gas\ rate(\frac{\$}{\text{therms}}) \tag{2}$$

3.5.2 Material and labor costs

The Building Component Cost Community Database (BC3) is a component cost database created by the NREL, Faithful+Gould, and the DOE to establish cost estimates for building components such as roof materials, insulation, fenestration, and other energy efficiency measures. The BC3 reports that the material costs are \$1.19/ft^2 for painting a cool roof. Furthermore, the labor costs are listed as $1.31/ft^2 and the combined material and labor costs are $2.5/ft^2 (BC3, 2012).

Table 3.5 breaks down the different types of material and labor costs that are used in this study. In determining the materials and labor cost, it was assumed that the homeowner hired a professional to purchase both the materials and to provide the labor for painting the cool or medium roof.

For the material cost, it was assumed that the homeowner only purchased the materials for a cool or medium roof. Therefore, the roof was painted either by the homeowner or by someone who had volunteered to do it for free for the homeowner such as a friend or a relative.

Table 3.5
Material and labor costs (BC3, 2012)

Types of Cost	Total Area (ft^2)	$/ft^2.	Total Cost ($)
Materials & Labor	1,200	2.5	$3000.00
Materials	1,200	1.19	$1,428.00
Premium Cost	1,200	0.10	$120.00

The Merrill Edge Report is a nationwide survey conducted by Bank of America that is aimed at consumers with financial assets between $50,000 and $250,000. Rismedia (2014) reports that, according to a Merrill Edge Report, 70% of homeowners are willing to partake in a do-it-yourself (DIY) home project when it reduces the cost for the project. Therefore, labor costs were eliminated for those that are interested in doing a DIY home project on the roof.

Finally, for each cost, the cool roof was evaluated with a premium cost. The EPA suggests that the cost premium for cool roofs versus conventional roofing materials ranges from 5 to 10 cents per sq. ft. for most products. Therefore, this was used to compare how the cool roof would perform against the medium roof with the application of the premium cost of $\$0.10/\text{ft}^2$ (EPA, 2013).

3.6 Environmental analysis

The environmental analysis was used to investigate the CO_2 emissions in this study. The EPA reports that one kWh equals 0.7 kg in CO_2 emissions and one therm equals 5.3 kg in CO_2 emissions. Therefore, Equations 3 and 4 illustrate the calculations for the CO_2 emissions of the electricity and natural gas consumption for the cool, medium, and dark roofs in each climate zone (EPA, 2014).

$$Electricity\ CO_2 = \text{kWh} \times 0.7\,\frac{\text{kg}}{\text{kWh}} \tag{3}$$

$$Natural\ Gas\ CO_2 = \text{therm} \times 5.3\,\frac{\text{kg}}{\text{therm}} \tag{4}$$

The EPA also reports that the average CO_2 emissions from energy use in a residential home is 10.12 metric tons CO_2, or 10,120 kg of CO_2 emissions. Equation 5 outlines the needed calculation to determine the annual CO_2 reduction for the cool roof and the medium roof in comparison to the dark roof.

$$Annual\ CO_2\ reduction(\%) = \frac{elec.\ CO_2 + nat.gas\ CO_2}{10.12\ \text{metric tons CO}_2} \times 100 \tag{5}$$

Based on the EPA greenhouse equivalence standard, one passenger vehicle is equal to 4,800 kg in CO_2 emissions, and the calculation is shown in Equation 6 (EPA, 2014).

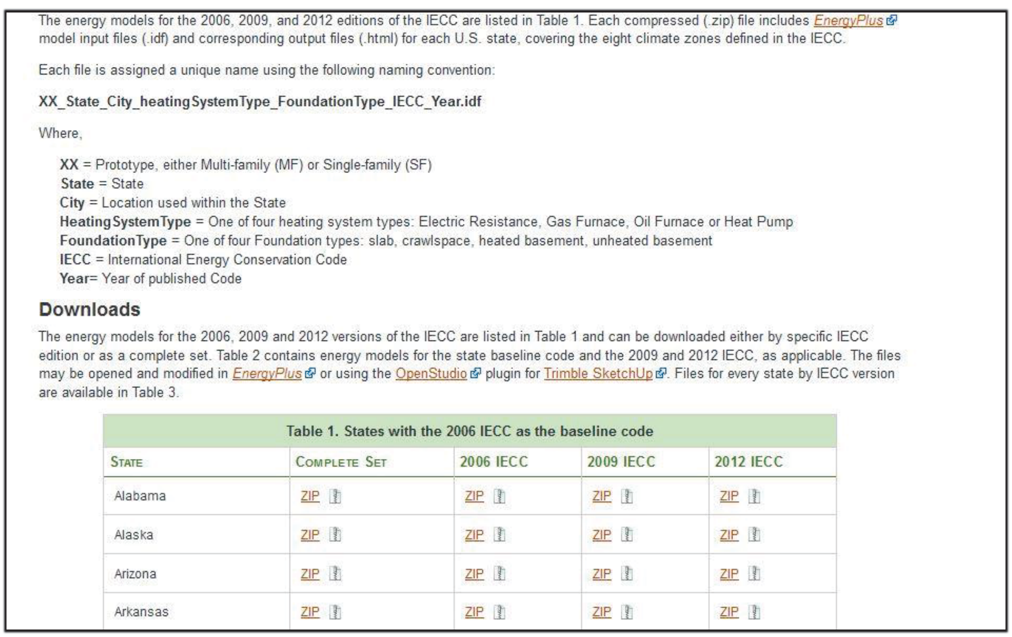
$$passenger\ cars = CO_2(\text{in kg}) \times \frac{1\ \text{car}}{4{,}800\ \text{kg}} \tag{6}$$

3.7 EnergyPlus process

This section discusses the process used with the EnergyPlus software for this study. By following this process, the data from this study can be replicated for future studies.

3.7.1 EnergyPlus residential benchmark database

After the location, heating system type, and foundation type were determined for each climate zone, the IECC 2009 model was used to represent the climate zone. The database and breakdown for each model is shown in Figure 3.2. After the models and the weather files for the selected locations were downloaded, the EnergyPlus software is now ready to be used for this study.



The energy models for the 2006, 2009, and 2012 editions of the IECC are listed in Table 1. Each compressed (.zip) file includes EnergyPlus model input files (.idf) and corresponding output files (.html) for each U.S. state, covering the eight climate zones defined in the IECC.

Each file is assigned a unique name using the following naming convention:

XX_State_City_heatingSystemType_FoundationType_IECC_Year.idf

Where,

XX = Prototype, either Multi-family (MF) or Single-family (SF)
State = State
City = Location used within the State
HeatingSystemType = One of four heating system types: Electric Resistance, Gas Furnace, Oil Furnace or Heat Pump
FoundationType = One of four Foundation types: slab, crawlspace, heated basement, unheated basement
IECC = International Energy Conservation Code
Year= Year of published Code

Downloads

The energy models for the 2006, 2009 and 2012 versions of the IECC are listed in Table 1 and can be downloaded either by specific IECC edition or as a complete set. Table 2 contains energy models for the state baseline code and the 2009 and 2012 IECC, as applicable. The files may be opened and modified in EnergyPlus or using the OpenStudio plugin for Trimble SketchUp. Files for every state by IECC version are available in Table 3.

Table 1. States with the 2006 IECC as the baseline code

State	Complete Set	2006 IECC	2009 IECC	2012 IECC
Alabama	ZIP	ZIP	ZIP	ZIP
Alaska	ZIP	ZIP	ZIP	ZIP
Arizona	ZIP	ZIP	ZIP	ZIP
Arkansas	ZIP	ZIP	ZIP	ZIP

Figure 3.2 EnergyPlus residential building benchmark database (U.S. BECP, 2013)

3.7.2 EP-Launch

The first screen that appears to the user when the EnergyPlus software opened is the EP-Launch, or EnergyPlus Launch screen. Figure 3.3 illustrates the EP-launch screen as shown to the user. The program has a variety of options available for the user. The single-input file enables the user to select one input file that contains the desired building model, a weather file, and the desired outputs for the results. The group of input files enables the user to group multiple input files together and simulate more than one building model at a time. The history tab shows the history of the simulated models, and the utilities section enables the user to search more options.

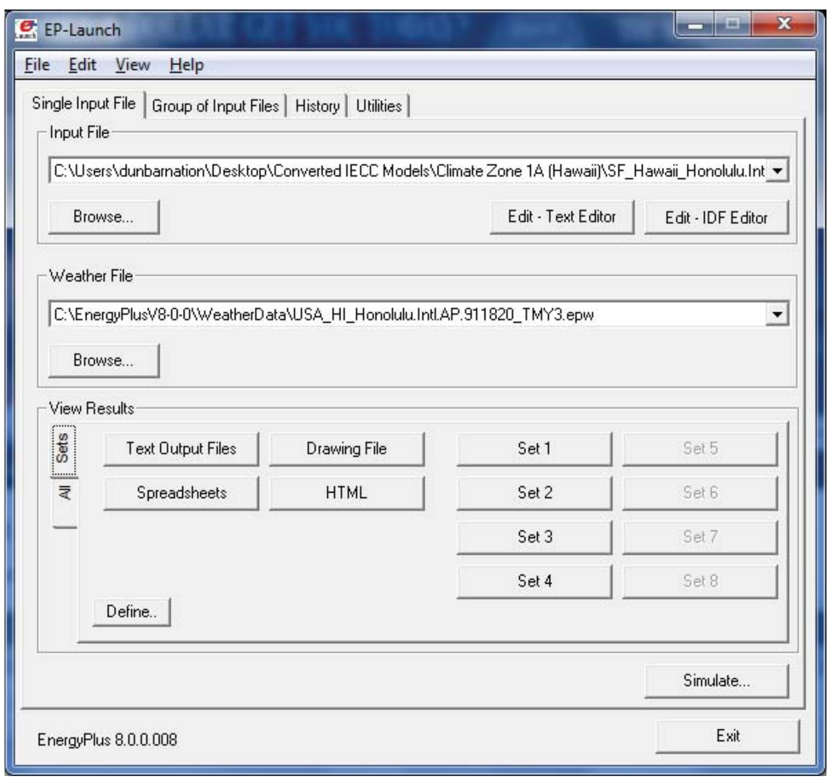


Figure 3.3 EP-Launch Screen

Figure 3.4 depicts the screen for the IDFVersionUpdater under the utilities tab in EP-Launch. The purpose of this utility is to update the building model from a previous EnergyPlus version to the current version. This option is crucial in this study because it enables the user to update the IECC models from version 5.0.0 to the version used in this study.

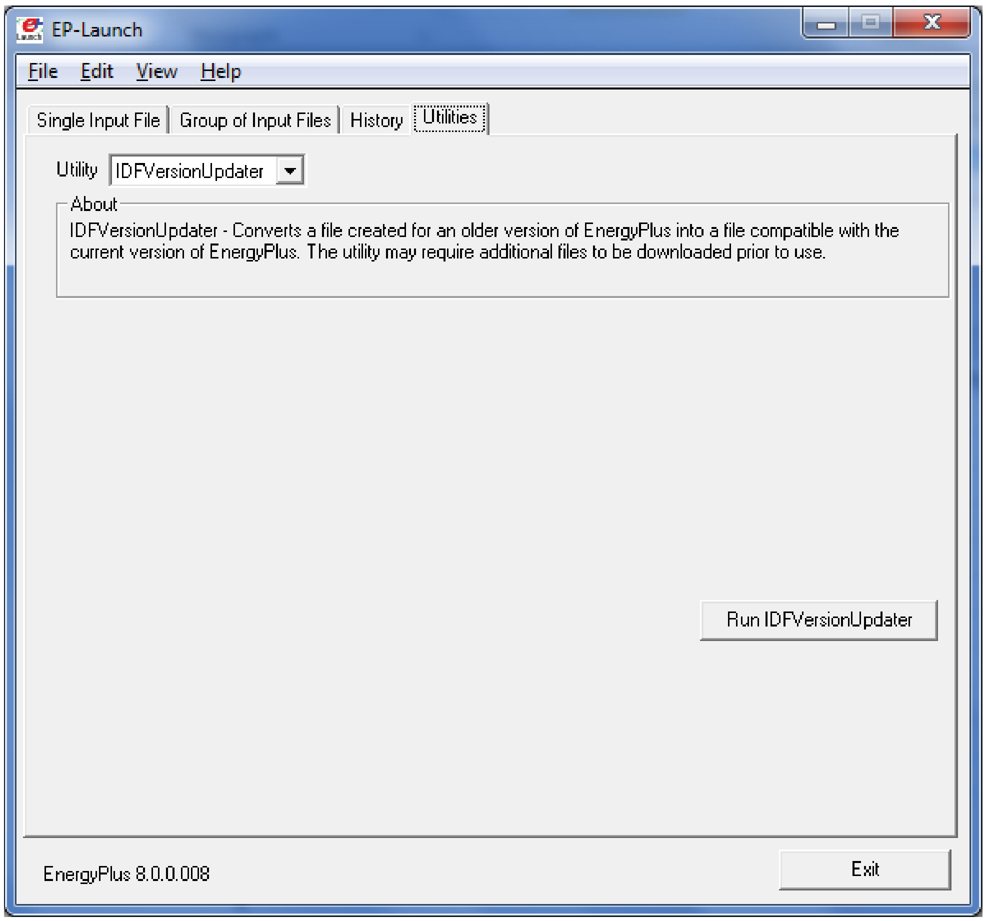


Figure 3.4 EnergyPlus IDFVersionUpdater

3.7.3 EnergyPlus IDF editor

The EnergyPlus IDF editor was used to demonstrate the characteristics of each building models (windows, walls, and roof). The screen for the IDF editor in the EnergyPlus software is illustrated in Figure 3.5.

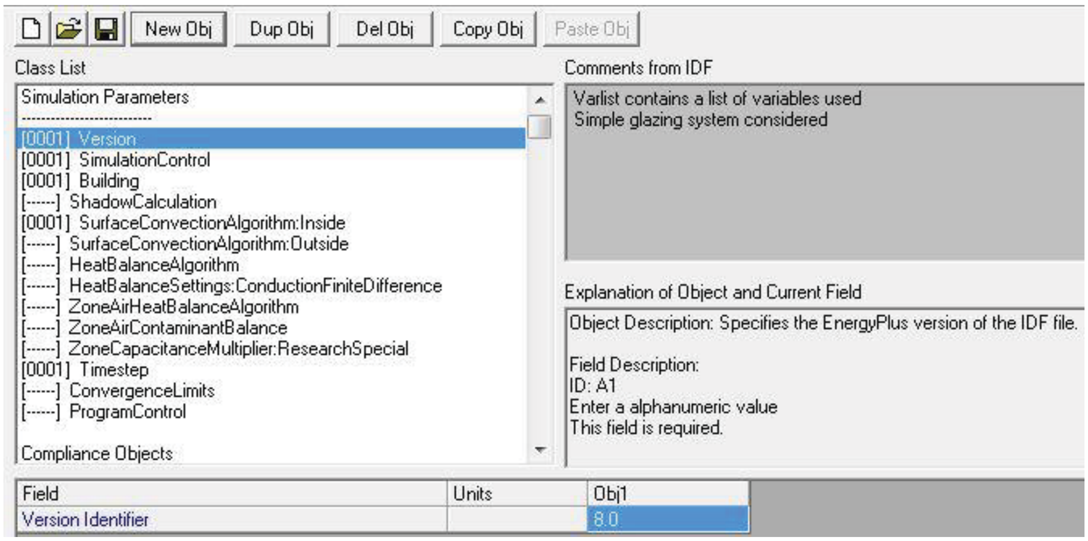


Figure 3.5 EnergyPlus IDF Editor

3.7.4 Change roof color in EnergyPlus software

The roof color of the building models in the EnergyPlus software was determined by the thermal absorptance, solar absorptance, and visible absorptance values. The thermal absorptance, or the emissivity, remained at 0.9 for all tests in this study. The solar and visible absorptance represented the absorptivity present in the material. The photograph in Figure 3.6 shows the inputted values for a cool roof in this study.

Field	Units	Obj12
Name		Asphalt_shingle
Roughness		MediumRough
Thickness	in	2.49600506E-01
Conductivity	Btu-in/h-ft2-F	5.67683773E-01
Density	lb/ft3	6.99999985E+01
Specific Heat	Btu/lb-F	3.00000002E-01
Thermal Absorptance		0.9
Solar Absorptance		0.2
Visible Absorptance		0.2

Figure 3.6 Roof color in the EnergyPlus software

3.7.5 EnergyPlus outputs

There are many variations of outputs in the EnergyPlus software. For this study, the electricity and natural gas outputs were viewed on a monthly basis.

[0002] Output:Meter
[------] Output:Meter:MeterFileOnly

Field Description: Form is EnergyUseType:....
eplusout.eso files

Field	Units	Obj1	Obj2
Name		Electricity:Facility	Gas:Facility
Reporting Frequency		Monthly	Monthly

Figure 3.7 EnergyPlus outputs

The output format used for this study was Excel for ease of use for further calculations, as shown in Table 3.6. The electricity and natural gas outputs in this study were reported monthly and used to determine the amount of energy used (kWh and therms), economic cost ($), and environmental impact (CO_2).

Table 3.6
EnergyPlus Microsoft Excel output file

Date/Time	Electricity:Facility [J](Monthly)	Gas:Facility [J](Monthly)
January	137,809,635	2,032,962,692
July	170,785,674	79,630,573
January	3,595,530,937	38,557,106,500
February	3,061,007,331	27,683,202,817
March	3,197,160,953	23,295,896,866
April	2,870,388,928	13,239,805,858
May	3,107,066,873	6,059,258,879
June	3,478,005,656	3,811,594,503
July	3,790,142,027	3,215,292,431
August	3,454,477,244	2,851,530,273
September	2,880,308,255	5,418,070,440
October	2,959,301,212	12,965,482,206
November	3,166,302,565	25,026,069,526
December	3,526,175,322	35,686,828,074

3.8 EnergyPlus benchmark model

Building America (BA) is a DOE research program developed by the industry that has accelerated the process for developing and adopting various building energy technologies in residential buildings, old and new. The National Renewable Energy Laboratory (NREL) developed the BA B10 Benchmark to track progress made with energy savings and to establish a benchmark residential building that was consistent with the 2009 IECC. This ensured that the results were not affected by a “moving target.” Furthermore, the benchmark was created for both single-family homes and multi-family homes. It contains occupancy schedules to represent the functions of typical occupants in a home (Hendron et al., 2010).

Figure 3.8 illustrates how the simulation model appears in the EnergyPlus software.

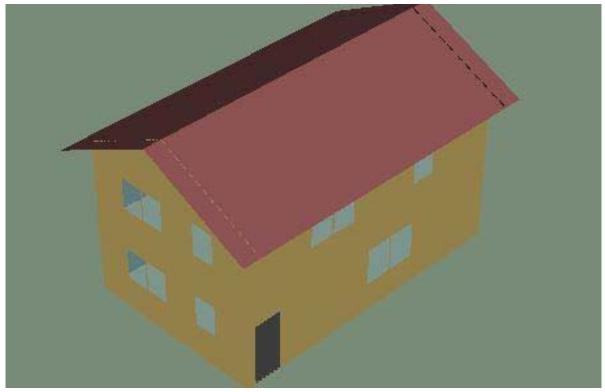


Figure 3.8 EnergyPlus simulation model

A full list of all the occupancy schedules for the appliances and the equipment of the IECC building models are listed in Appendix C. These schedules remain the same for all the IECC building models used in this study, since there is no IECC building standard for occupancy scheduling. Furthermore, the appendix also contains a breakdown of the changes in different materials for residential homes according to the U.S. climate zone.

Table 3.7 demonstrates a breakdown of the different parameters incorporated into every EnergyPlus simulation model in this study.

Table 3.7
Material breakdown of EnergyPlus simulation model (Taylor et al., 2012)

Parameter Type	Selected Parameter
Total house size (ft^2)	2,400-3,600 (1,200 ft^2 for basement)
Roof type	Steep-sloped
Default roof color	Dark
Internal heat gain	91,436 BTU/day
Hours of Operation	Yes (showers, laundry, and cooking)
Heating Type	Varied; 78% AFUE natural gas heater / 13 SEER electric heat pump
Air Conditioner	12 SEER central unit
Number of occupants	3
Interior Material	Drywall
Exterior Wall Type	Stucco
Number of Floors	2
Roof Material	Asphalt Shingles

The typical residential simulation model will consist of a dark color roof, central air conditioning unit, heating system, 3 occupants, and 2 floors. The listed parameters will remain the same for every building simulation model regardless of the climate zone location.

CHAPTER 4. ANALYSIS OF RESULTS

This section presents all the data and the findings in this study. It includes the energy analysis, economic analysis, and environmental impact of the cool roof and the medium roof of residential homes in each U.S. climate zone.

4.1 Determination of the cooling and the heating seasons

In the literature review, the heating and cooling seasons were often predetermined and assumed for the studies. For example, Lam et al. (2005) determined that the cooling season for his experiment in China was defined as May to October. However, there are two major differences between his study and this study. First, his study took place in China and only entailed one climate zone, whereas this study incorporated various climate zones.

In this study, therefore, the heating and the cooling seasons for the climate zones were determined by the monthly heating degree days (HDD) and the monthly cooling degree days (CDD) for each zone. If the HDD for the month was greater than the CDD, then the month was determined to be as a part of the heating season. In contrast, if the CDD for the month was greater than the HDD, then the month was determined to be a part of the cooling season.

The heating and the cooling seasons for the climate zones are shown in Table 4.1 for the ASHRAE standard. Typically, the analysis has the HDD and the CDD set to a base temperature of 65˚F (18.3˚C). These are the default base temperatures used for the HDD and the CDD calculations (Williams, 1994). However, the analysis in this study was based on the 2009 ASHRAE standard for the HDD and the CDD degree day with respect to climatic conditions. The HDD was set to a base temperature of 50˚F (10˚C), and the CDD was set to a base temperature of 65˚F (18.3˚C). The purpose of using the ASHRAE standard is because the EnergyPlus software uses it to determine the climatic conditions of a location.

Table 4.1
Climate zone heating and cooling seasons

	HDD @ 10˚C (50˚F)	CDD @ 18.3˚C (65˚F)
All Climate Zones	Heating	Cooling
1A	No season	All Year
2A	No season	All Year
2B	December	Jan-Nov
3A	Nov-Mar	Apr-Oct
3B	No season	All Year
3C	Dec-Mar	Apr-Nov
4A	Nov-Mar	Apr-Oct
4B	Nov-Apr	May-Oct
4C	Oct-Apr	May-Sep
5A	Nov-Apr	May-Oct
5B	Oct-Apr	May-Sep
6A	Oct-Apr	May-Sep
6B	Oct-May	June-Sep
7	Oct-May	June-Sep
8	Sep-May	June-Aug

Desjarlais reported that the heating load increased costs in the winter with the cool roof (Desjarlais et al., 2007). Therefore, based on this, the cool roof and the medium roof should become less efficient as the climate becomes colder.

4.2 Energy consumption

The purpose of this section is to determine the amount of electricity and natural gas consumed in a residential home in each U.S. climate zone. The data in this section were used as the reference points for the simulation models of each U.S. climate zone for the analyses assessed further in this chapter.

Figure 4.1 demonstrates the annual electricity consumption for the dark roof in each climate zone. The two climate zones with the highest electricity outputs are 2A and 4A. These are not anomalies because these are the only two climate zones that have electric heating systems.

Therefore, both the heating and cooling loads for these climate zones were outputted for the electricity consumption. However, besides those two climate zones, the data suggest that electricity consumption is higher for the warmer climate zones, such as 1A, 2B, and 3A, than for the other climate zones.

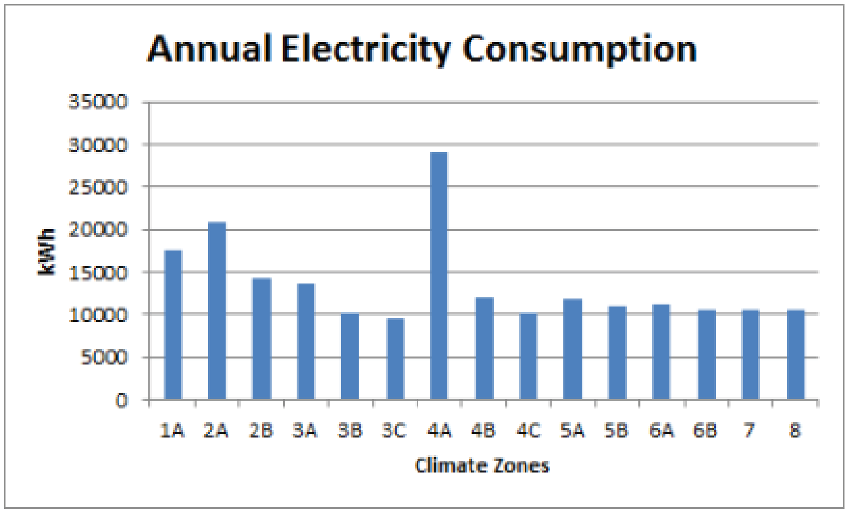


Figure 4.1 Annual electricity consumption for each climate zone

The annual natural gas consumption for the dark roof in each climate zone is shown in Figure 4.2. The natural gas output is higher for the colder climates, such as climate zones 7 and 8, than the other climate zones. As noted earlier, climate zones 2A and 4A do not have gas heating systems. Therefore, these climate zones outputted 0 therms for the natural gas load.

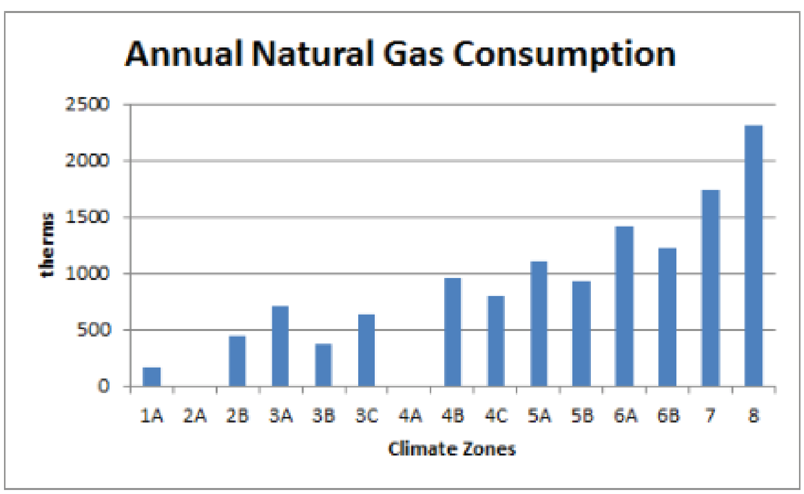


Figure 4.2 Annual natural gas consumption for each climate zone

Table D.1 and Table D.2 in Appendix D lists the electricity consumption, in kWh, and the natural gas consumption, in therms, for each roof color of the respective climate zone.

4.3 Economic analysis

In this section, an economic analysis was performed with the results of the energy savings, SPP, and the NPV. Table 4.2 presents the electrical and natural gas cost for each climate zone in this study. There is no natural gas cost for climate zone 2A and 4A since there are no natural gas heating systems.

A breakdown of all the electricity costs and natural gas costs for each climate zone is presented in Table 4.2. These costs were provided by the Energy Information Agency (EIA).

Table 4.2

Electricity and natural gas costs (Energy Information Agency, 2014, 2013)

All Climate Zones	Location	Natural Gas ($/therm)	Electric Cost ($/kWh)
1A	Honolulu, HI	$5.17	$0.3750
2A	Tampa, FL	$0.00	$0.1139
2B	Houston, TX	$1.03	$0.1097
3A	Wichita Falls, TX	$1.03	$0.1097
3B	Los Angeles, CA	$0.89	$0.1536
3C	San Francisco, CA	$0.89	$0.1536
4A	Richmond, VA	$0.00	$0.1118
4B	Philadelphia, PA	$1.17	$0.1278
4C	Seattle, WA	$1.16	$0.0852
5A	Harrisburg, PA	$1.17	$0.1278
5B	Colorado Springs, CO	$0.81	$0.1151
6A	Madison, WI	$0.91	$0.1326
6B	Cheyenne, WY	$0.82	$0.0982
7	Duluth, MN	$0.78	$0.1143
8	Fairbanks, AK	$0.83	$0.1809

Hawaii, in climate zone 1A, had the highest cost for both natural gas and electricity. Furthermore, Alaska, in climate zone 8, had the second highest cost for electricity.

4.3.1 Energy results

In this section, the electricity, natural gas, and overall energy results are documented for the roof colors. The electricity results documents the electricity savings and losses for each climate zone of the cool roof and the medium roof. The natural gas results documents the natural gas savings and losses for each climate zone of the cool roof and the medium roof. The energy results are the summation of the electricity and natural gas results.

4.3.1.1 Annual electricity comparison

The annual electricity comparison for each climate zone is presented in Figure 4.3. The provided data supports what the research has suggested cool roofs and that they are beneficial to air-conditioning and electricity costs. The highest amount of savings was demonstrated in climate zone 1A at $140.00/year. There were electricity savings exhibited for the colder climates in zones 6, 7, and 8.

The electricity analysis was primarily focused on the air-conditioning savings. The two exceptions to this statement are climate zones 2A and 4A because these zones use electric heat pumps as the heating system.

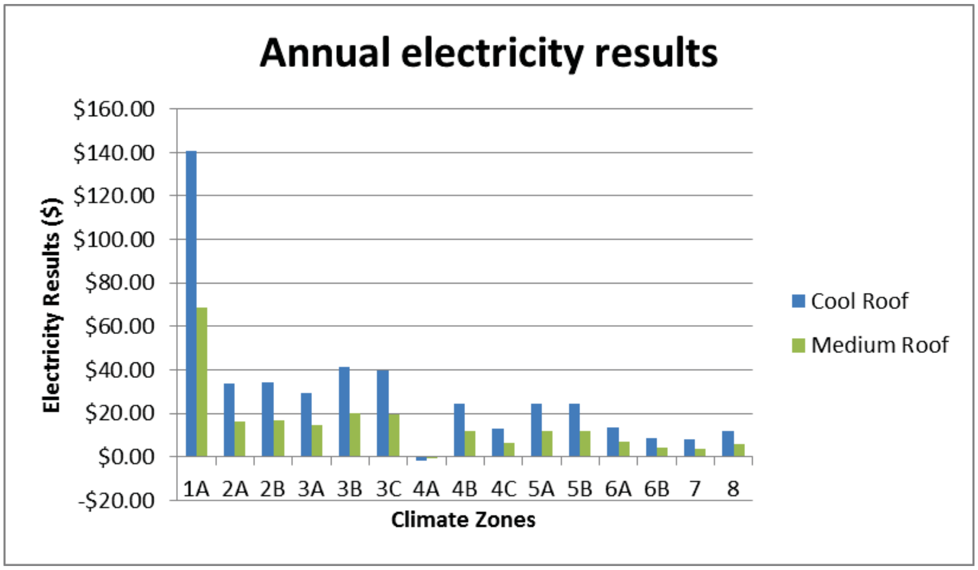


Figure 4.3 Annual electricity results

4.3.1.2 Annual natural gas comparison

The annual natural gas results for each climate zone are presented in Figure 4.4. The research earlier in this study suggested that cool roofs increased heating load costs in the winter (Desjarlais et al., 2007).

Since natural gas was primarily used for heating functions, this explained why the cool roof and the medium roof had a negative economic impact on the residential buildings.

As noted earlier, climate zones 2A and 4A do not have a natural gas heater. Therefore, there are no results present to compare to the dark roof, hence why each has $0 on the graph.

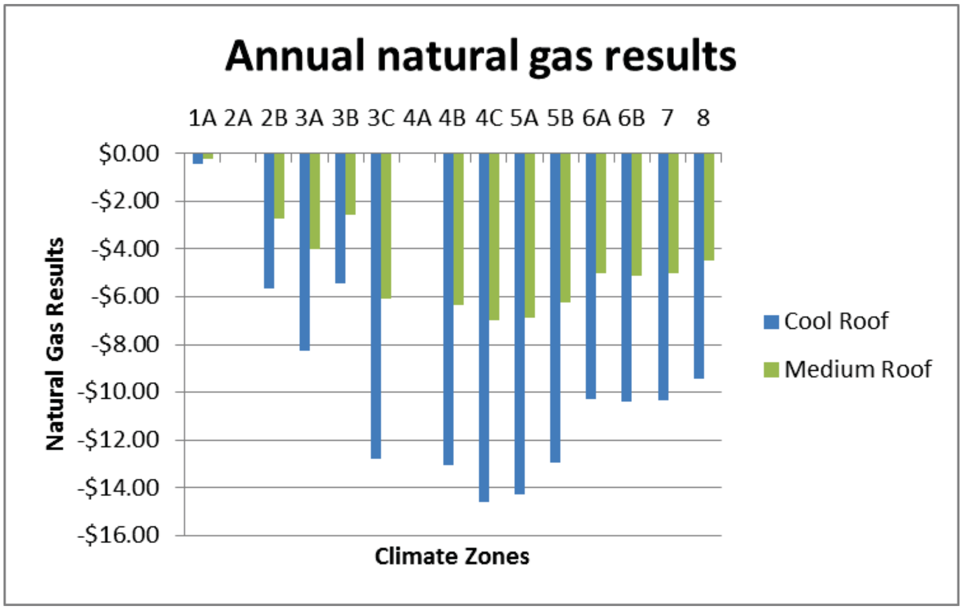


Figure 4.4 Annual natural gas comparison

4.3.1.3 <u>Annual energy results</u>

The annual energy savings in this study are the summation of the annual natural gas savings and the annual electricity savings. The graph in Figure 4.5 demonstrates the annual energy savings for each climate zone in this study. Overall, in terms of energy savings, cool roofs perform well in most climate zones, including colder climate zones.

Climate zone 8 exhibits some energy savings, whereas warmer climates, such as 4A, 4C, 6B, and 7, exhibit energy losses. Another important finding is that, in climate zones 4A, 4C, 6B, and 7, the medium roof performs better than the cool roof. Both roofs exhibit annual energy losses for the respective climate zones.

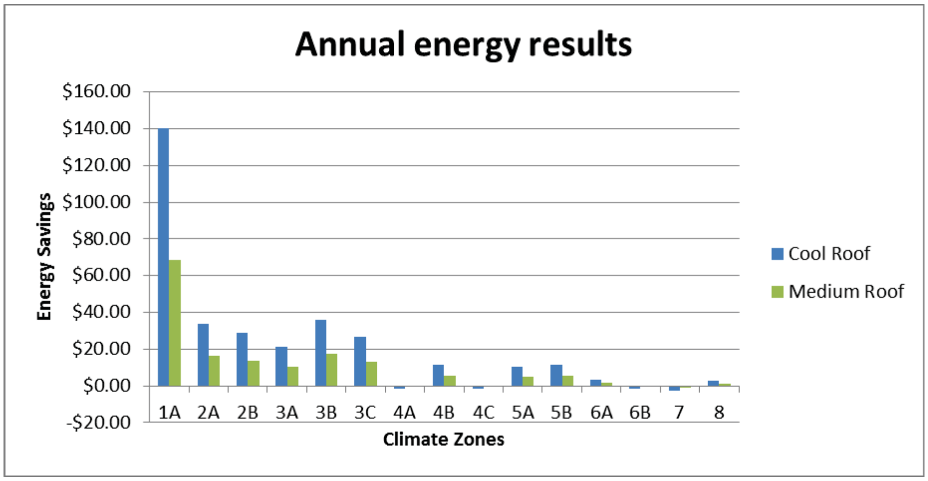


Figure 4.5 Annual energy results

Table 4.3 outlines the percentage of the overall energy savings of the cool roof and the medium roof in terms of the overall energy cost for a residential home in each U.S. climate zone.

Table 4.3
Percentage savings on overall energy cost (%)

All Climate Zones	Cool Roof	Medium Roof
1A	1.93	0.93
2A	1.45	0.69
2B	1.45	0.69
3A	0.96	0.47
3B	1.49	0.73
3C	1.27	0.63
4A	-0.05	-0.02
4B	0.44	0.21
4C	-0.09	-0.04
5A	0.37	0.18
5B	0.58	0.28
6A	0.13	0.06
6B	-0.08	-0.04
7	-0.10	-0.05
8	0.07	0.03

The results suggest that the maximum percentage savings of the overall energy cost that can be experienced with the cool roof is 1.93% and 0.93% with the medium roof, respectively.

4.3.2 SPP

The SPP is the amount of time that it takes for the initial cost to be recouped from an investment. Equation 7 demonstrates the default equation for the SPP (Payback Period, 2014). Equation 8 demonstrates how the SPP is utilized in this study.

$$SPP = \frac{Initial\ Investment}{Recurring\ benefits} \tag{7}$$

$$SPP = \frac{material\ and\ labor\ costs}{annual\ energy\ savings} \tag{8}$$

There were three tests for the SPP. The first test assessed when the initial investment only consisted of the material costs. The second test assessed when the initial investment consisted of both the material and the labor costs. The third test assessed only the premium cost of the cool roof. The recurring benefits in the tests were the annual energy savings for each model. The payback period for the residential buildings in climate zones 4A, 4C, 6B, and 7 was set to 0 because an energy loss resulted when the cool roof was implemented. Thus, the payback period was not attainable for these climate zone locations.

4.3.2.1 SPP with material and labor costs

This section focuses on the SPP for the residential building in each climate zone when the material and labor costs are assessed.

Table 4.4 presents the results for the SPP with material and labor costs. The payback period for the residential buildings in climate zones 4A, 4C, 6B, and 7 was set to 0 because an energy loss resulted when the cool roof was implemented. Thus, the payback period was not attainable for these climate zone locations. Climate Zone 1A had the smallest payback period of 21.39 years for a cool roof, 22.24 years when the premium for the cool roof was added, and 43.86 years for the medium roof. Other than that, climate zone 2A was the only other zone that produced a payback period less than 100 years for a cool roof. Even with the premium cost added, the cool roof performs better than the medium roof in each applicable climate zone.

Table 4.4
SPP (material & labor cost) (in years)

All Climate Zones	Cool Roof	Premium Added	Medium Roof
1A	21	22	43
2A	88	92	183
2B	104	108	216
3A	141	147	289
3B	83	87	170
3C	112	116	225
4A	N/A	N/A	N/A
4B	259	269	534
4C	N/A	N/A	N/A
5A	293	304	606
5B	258	269	529
6A	865	900	1,759
6B	N/A	N/A	N/A
7	N/A	N/A	N/A
8	1,144	1,190	2,272

4.3.2.2 SPP with material cost

This test assessed the SPP with the incorporation of solely the materials cost for the cool roof and the medium roof of the residential buildings in each climate zone.

Table 4.5 presents the results for the SPP of the material cost. The results in this table are more favorable for the cool roof and the medium roof than the results for the material and labor costs. The payback period for the residential buildings in climate zones 4A, 4C, 6B, and 7 was set to 0 because an energy loss resulted when the cool roof was implemented. Thus, the payback period was not attainable for these climate zone locations. Four climate zones present a payback period of less than 50 years for a cool roof, including a low of 10 years for climate zone 1A. Additionally, the medium roof has a payback period of 20 years for climate zone 1A, but did not have any other zones with a payback period under 50 years. Similar to the previous section, a cool roof, even with a premium, performs better than the medium roof in each climate zone.

Table 4.5
SPP (material cost) (in years)

All Climate Zones	Cool Roof	Premium	Medium Roof
1A	10	11	20
2A	42	45	87
2B	49	53	103
3A	67	73	137
3B	39	43	81
3C	53	57	107
4A	N/A	N/A	N/A
4B	123	133	254
4C	N/A	N/A	N/A
5A	139	151	288
5B	123	133	251
6A	412	446	837
6B	N/A	N/A	N/A
7	N/A	N/A	N/A
8	545	590	1,081

4.3.2.3 SPP with premium cost

This test focuses on accumulating the SPPs for each climate zone when accounting for only the premium cost of the cool and medium roof. Previously, the premium cost was determined in Table 3.5 as $120. Table 4.6 presents the results for SPPs with the assessment of the premium cost of the cool roof.

Besides climate zones 5A, 6A, and 8, the SPPs for most of the climate zones were less than 10 years. In fact, climate zone 1A registered the lowest SPP at less than a year.

This suggests that the cool roof can provide a return on investment, even when the premium cost was added.

Table 4.6
SPP (premium cost) (in years)

All Climate Zones	Cool Roof
1A	<1
2A	3
2B	4
3A	5
3B	3
3C	4
4A	N/A
4B	10
4C	N/A
5A	11
5B	10
6A	35
6B	N/A
7	N/A
8	46

4.3.3 NPV

The NPV was used to determine the profitability of an investment. Therefore, in this study, the NPV was used to analyze the profitability of cool and medium roofs in the different climate zones. Furthermore, the premium cost was also taken into account to determine if the cool roof became a less favorable option. Equation 9 presents the equation for the NPV (Net Present Value, 2014).

$$NPV = \sum_{t=1}^{T} \left(\frac{C_t}{(1+r)^t} \right) - C_0 \tag{9}$$

In this study, C_t is the annual energy savings recurring for the time period, r is the discount rate of 5%, t is 10 years, and C_0 is the initial investment cost.

For this section, the NPV is evaluated three times depending on the following investment costs: material and labor, and only material.

4.3.3.1 NPV for material and labor costs

Table 4.7 demonstrates the results for the NPV when the material and the labor costs are taken into account. As noted earlier, the material and the labor costs combined were $3,000. The data suggested that neither the cool roof nor the medium roof is a profitable investment in any of the climate zones.

It has been well documented that cool roofs can save building owners money every year. However, as shown in this study, the savings are not enough to cover the material and the labor costs for installing the roof color coating. Furthermore, the economic losses for the application of a cool roof ranged between $1,664 and $3,144, depending on if the premium cost was also added. The economic losses from the medium roof ranged between $2,348 and $3,011.

Therefore, the homeowner can expect an additional cost as much as $663 with the application of the medium roof in a particular climate zone. Likewise, the homeowner can expect an additional cost as much as $1,360 with the application of the cool roof in a particular climate zone.

Table 4.7
NPV of material & labor cost ($)

All Climate Zones	Cool Roof	Premium	Medium Roof
1A	-$1,664	-$1,784	-$2,348
2A	-$2,678	-$2,798	-$2,844
2B	-$2,725	-$2,845	-$2,868
3A	-$2,798	-$2,918	-$2,901
3B	-$2,659	-$2,779	-$2,832
3C	-$2,745	-$2,865	-$2,873
4A	-$3,016	-$3,136	-$3,007
4B	-$2,889	-$3,009	-$2,946
4C	-$3,015	-$3,135	-$3,006
5A	-$2,902	-$3,022	-$2,952
5B	-$2,889	-$3,009	-$2,945
6A	-$2,967	-$3,087	-$2,983
6B	-$3,015	-$3,135	-$3,007
7	-$3,024	-$3,144	-$3,011
8	-$2,975	-$3,095	-$2,987

4.3.3.2 NPV for material cost

In the previous section, the results showed that neither the cool roof savings nor the medium roof savings are sufficient to cover the material and the labor installation cost. Therefore, in this section, the study investigates whether the cool roof and the medium roof are profitable for residential buildings in each climate zone when only the material cost are taken into account. The findings in this section are found in Table 4.8.

Although only the material cost was analyzed in this section, the NPV results suggest that neither the medium roof nor the cool roof were profitable for a residential building in any U.S. climate zone location.

Table 4.8
NPV of material cost ($)

All Climate Zones	Cool Roof	Premium	Medium Roof
1A	-$92	-$212	-$776
2A	-$1,106	-$1,226	-$1,272
2B	-$1,153	-$1,273	-$1,296
3A	-$1,226	-$1,346	-$1,329
3B	-$1,087	-$1,207	-$1,260
3C	-$1,173	-$1,293	-$1,301
4A	-$1,444	-$1,564	-$1,435
4B	-$1,317	-$1,437	-$1,374
4C	-$1,443	-$1,563	-$1,434
5A	-$1,330	-$1,450	-$1,380
5B	-$1,317	-$1,437	-$1,373
6A	-$1,395	-$1,515	-$1,411
6B	-$1,443	-$1,563	-$1,435
7	-$1,452	-$1,572	-$1,439
8	-$1,403	-$1,523	-$1,415

The only climate zone that did not incur over $1,000 in economic losses for the 10-year period was 1A, which reported a loss of $92 with the cool roof, a loss of $212 with the additional premium cost, and a loss of $776 for the medium roof.

4.4 Environmental impact

In this section, the overall environmental impact of the cool roof and the medium roof is evaluated. First, the CO_2 emissions savings are evaluated for the cool and the medium roofs of the residential building in each climate zone. Next, the results are compared to determine the CO_2 passenger car equivalent to the results for the CO_2 emissions savings. Finally, the environmental impact is analyzed on a larger scale with the total amount of occupied detached houses in the U.S., as reported by the U.S. census, included in the analysis.

4.4.1 Electricity CO_2 emissions

Figure 4.6 demonstrates the annual CO_2 emissions for electricity consumption. Except for climate zone 4A, the hot climates, such as 1A and 2A, produce more CO_2 than the other climate zones. The marine climate zones in 3C and 4C produce the least amount of CO_2, including less than all the cold climate zones, such as 7 and 8.

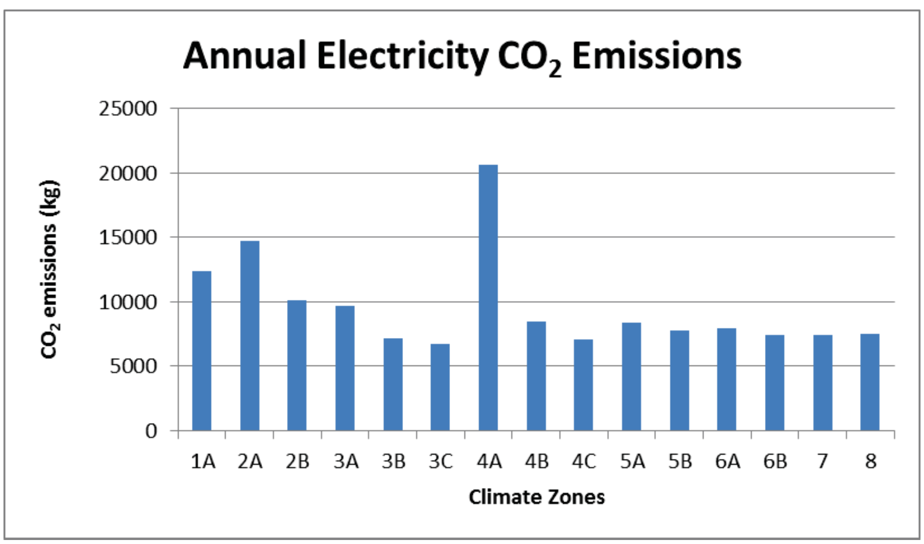


Figure 4.6 Annual electricity CO_2 emissions

4.4.2 Annual natural gas CO_2 emissions

Figure 4.7 demonstrates the findings for the annual natural gas CO_2 emissions. Climate zones 2A and 4A produce 0 emissions because they only utilize electric systems. The data in this study suggest that the CO_2 consumption of natural gas increases for colder climate zones.

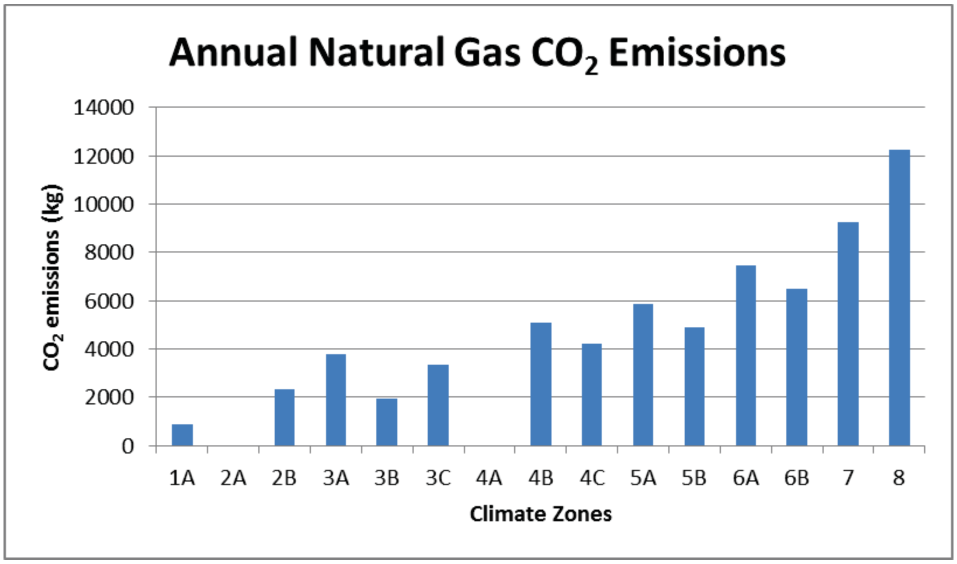


Figure 4.7 Annual natural gas CO_2 emissions

Overall, the moist (A) climates produce the most CO_2 emissions for this section, followed by the dry (B) and the marine (C) climates. The residential building in climate zone 8 exhibits the highest amount of CO_2 emissions for the natural gas system, while the one in climate zone 1A exhibits the lowest.

4.4.3 Annual CO_2 emissions comparison

The annual CO_2 consumption consists of the summation of the natural gas CO_2 emissions and the CO2 emissions from the electricity consumption. Figure 4.8 demonstrate the results for each climate zone concerning the annual CO_2 emissions.

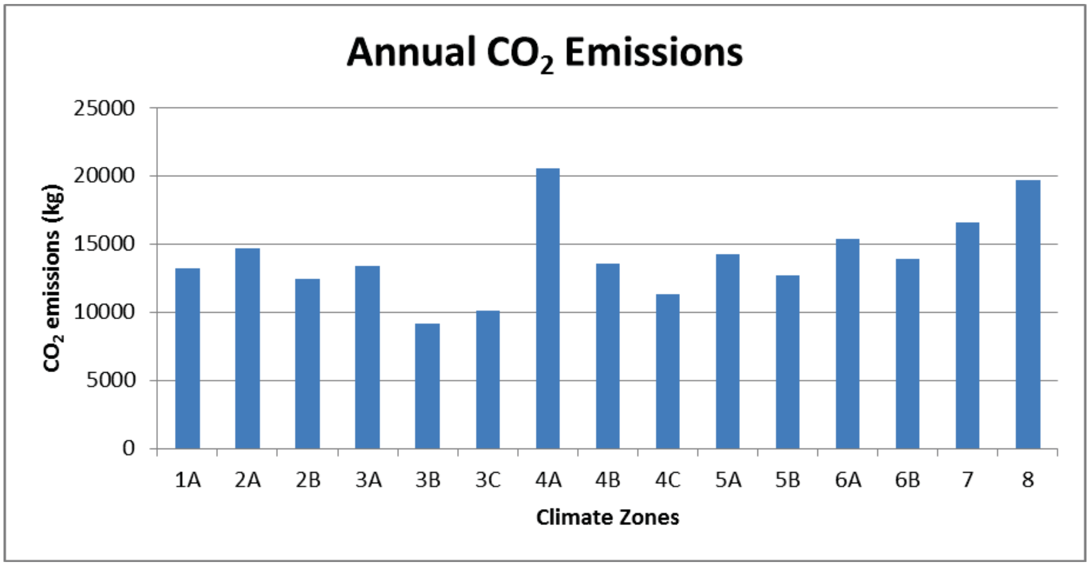


Figure 4.8 Annual CO_2 emissions

There appears to be more CO_2 emissions in the colder climates, such as zones 7 and 8, than in the warmer climates, such as 1A and 2A. Perhaps this suggests that natural gas heating systems produce more CO_2 per unit than electricity.

4.4.4 CO_2 emissions savings

Figure 4.9 demonstrates the annual CO_2 savings for each climate zone. The data suggest that the cool roof and the medium roof produce CO_2 savings in the warm to hot climates. In contrast, both roof options produce negative CO_2 savings in colder climates, such as 6B, 7, and 8.

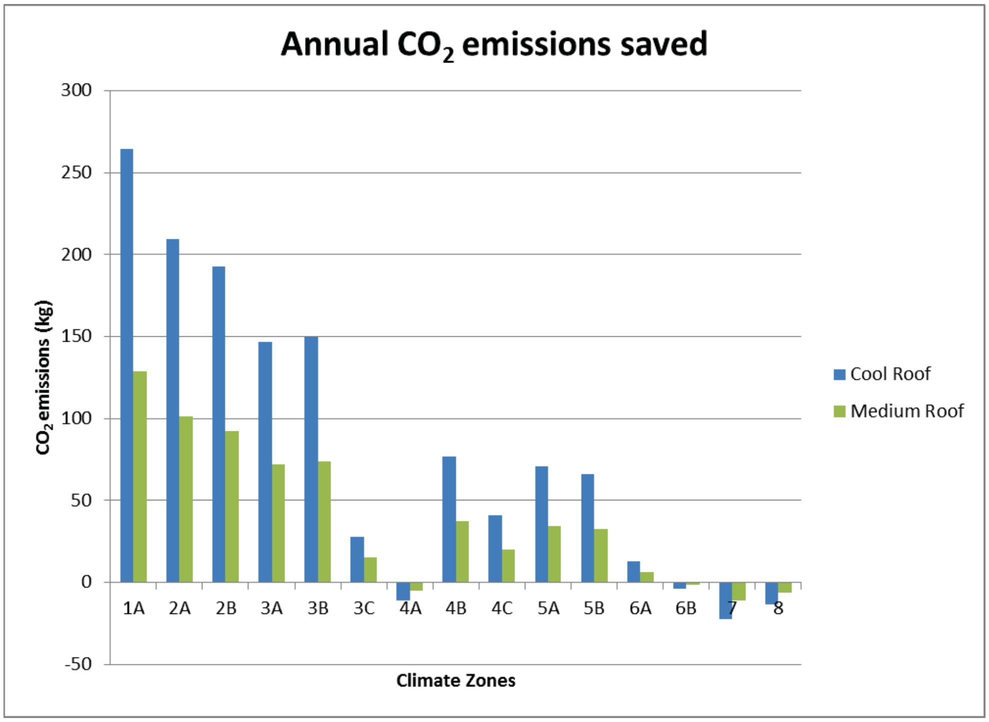


Figure 4.9 Annual CO_2 emissions saved

The climate-dependent aspect for cool roofs and medium roofs are apparent in this section. Climate zone 1A saves 10 times more CO_2 emissions annually than climate zone 3C for a cool and medium roof.

4.4.5 CO_2 emissions and reduction of passenger cars

The CO_2 emissions savings are a great tool to have for determining the environmental impact of changes represented by the cool roof and the medium roof.

However, it is difficult to quantify the significance without a greenhouse equivalence standard. Therefore, with the EPA greenhouse equivalence standard, this section evaluates the significance of the CO_2 emissions by comparing them to the equivalent in passenger car emissions.

Table 4.9 lists the data for the reduction of passenger cars annually for one home in each climate zone. Both the cool roof and the medium roof perform best in climate zone 1A.

However, the savings to the environment are not significant. The cool roof reduces the CO_2 emissions equivalent to 0.05 passenger cars, and the medium roof reduces the CO_2 emissions to the equivalent of 0.026 passenger cars.

Table 4.9

CO_2 emissions saved annually in the U.S.

All Climate Zones	Cool Roof		Medium Roof	
	Cars removed	CO_2 emissions saved (kg)	Cars removed	CO_2 emissions saved (kg)
1A	0.053	264	0.026	129
2A	0.042	209	0.020	101
2B	0.039	193	0.019	93
3A	0.029	147	0.014	72
3B	0.030	150	0.015	74
3C	0.006	28	0.003	15
4A	-0.002	-11	-0.001	-5
4B	0.015	77	0.007	37
4C	0.008	41	0.004	20
5A	0.014	71	0.007	34
5B	0.013	66	0.006	32
6A	0.003	13	0.001	6
6B	-0.001	-4	0.000	-1
7	-0.004	-22	-0.002	-11
8	-0.003	-13	-0.001	-6

Table 4.10 shows the percentage of CO_2 emissions saved by a cool roof and a medium roof on the annualized CO_2 emissions average of a residential home in each U.S. climate zone.

Table 4.10
Percentage of CO_2 emissions saved of the annualized average CO_2 emissions of a U.S. residential home (%)

All Climate Zones	Cool Roof	Medium Roof
1A	2.52%	1.23%
2A	1.99%	0.96%
2B	1.84%	0.88%
3A	1.40%	0.69%
3B	1.42%	0.70%
3C	0.27%	0.15%
4A	N/A	N/A
4B	0.73%	0.36%
4C	0.39%	0.19%
5A	0.67%	0.33%
5B	0.63%	0.31%
6A	0.12%	0.06%
6B	N/A	N/A
7	N/A	N/A
8	N/A	N/A

The results suggest that neither the cool roof nor the medium roof have a significant impact on the reduction of CO_2 emissions of a single residential home. For the cool roof, the highest reported savings are 2.52% in climate zone 1A, and the lowest savings are reported at 0.12% in climate zone 6A. For the medium roof, the highest reported savings are 1.23% in climate zone 1A, and the lowest savings are reported at 0.06% in climate zone 6A.With the exclusion of the marine zones, the data demonstrate a linear decrease in the reported savings as the climate zone became colder.

Furthermore, the amount of passenger cars reduced in each climate zone after 10 years was shown in Table 4.11. More than half the climate zones produce CO_2 emissions savings equivalent of more than 10% of a passenger car for a cool roof. Then, 33% of the climate zones save the CO_2 equivalent of more than 10% of a passenger car for the medium roof. Therefore, the data suggest that the cool roof and the medium roof do exhibit a positive impact on the environment over the dark roof.

Table 4.11
Amount of passenger cars removed in the U.S. after 10 years

All Climate Zones	Cool Roof		Medium Roof	
	Cars removed	CO_2 emissions saved (kg)	Cars removed	CO_2 emissions saved (kg)
1A	0.53	2,645	0.26	1,290
2A	0.42	2,093	0.20	1,011
2B	0.39	1,928	0.19	926
3A	0.29	1,470	0.14	720
3B	0.30	1,495	0.15	737
3C	0.06	278	0.03	153
4A	-0.02	-110	-0.01	-50
4B	0.15	770	0.07	374
4C	0.08	408	0.04	200
5A	0.14	708	0.07	342
5B	0.13	661	0.06	323
6A	0.03	131	0.01	65
6B	-0.01	-41	0.00	-15
7	-0.04	-222	-0.02	-107
8	-0.03	-133	-0.01	-61

Table 4.12 lists the number of cool roof homes needed to remove one passenger car from the road every year. Climate zones 1A and 2A suggests that 19 and 24 homes, respectively, need to be equipped with cool roofs to reduce the CO_2 emissions equivalent to one passenger car per year in each area. Furthermore, medium roofs need to be applied to 39 and 49 homes in these zones to achieve a CO_2 reduction equivalent to one

passenger car per year. Climate zone 3C requires 180 homes, and climate zone 4C requires 123 homes for the reduction of CO_2 emissions equivalent to one passenger car. In contrast, the negative numbers are valid values and indicate the number of homes that are needed to increase the CO_2 emissions equivalent to a passenger car.

Table 4.12
Number of homes required to remove the CO_2 *emissions equivalent of one passenger car*

All Climate Zones	Cool Roof	Medium Roof
1A	19	39
2A	24	49
2B	26	54
3A	34	69
3B	33	68
3C	180	326
4A	-456	-1004
4B	65	134
4C	123	250
5A	71	146
5B	76	155
6A	383	774
6B	-1224	-3404
7	-225	-466
8	-376	-826

Therefore, for climate zone 4A, 456 homes would need to switch to cool roofs to add one passenger car's worth of CO_2 emissions. Furthermore, it would take 1,004 homes to switch to a medium roof to add the same effect in climate zone 4A.

CHAPTER 5. CONCLUSION

5.1 Summary

This study was designed to be an energy analysis of the implementation of cool roofs and medium roofs on residential buildings in the United States. In addition, an economic analysis was conducted, which focused on the feasibility of the cool roof and the medium roof taking the initial costs into consideration. The environmental impact was also analyzed by reviewing the energy consumption data for electricity and natural gas. The reduction of the CO_2 emissions was analyzed by comparing the equivalent amount of passenger cars being removed from the road.

5.2 Outcomes

1. The cool roof produces more energy savings than the medium roof, when compared to the dark roof, in all of the climate zones except 4A, 4C, 6B, and 7 due to warm climates and high electricity costs. The energy savings of the cool roof and the medium roof do not appear to be significant but the highest reported savings was achieved in climate zone 1A at 1.93% and 0.93%, respectively.
2. When the material and the labor costs are considered, neither the cool nor the medium roof produce an SPP of less than 10 years for any U.S. climate zone

location. Therefore, the homeowner would not break even over the typical lifespan of the roof coating.

3. When solely the material costs are included, the NPV results suggest that neither the cool roof nor the medium roof were profitable options for any U.S. climate zone location.
4. The largest CO_2 emissions reduction is reported as 2.52% in climate zone 1A for the cool roof and 1.23% in climate zone 1A for the medium roof.
5. The implementation of the cool roof on a single residential home removes a maximum of 264 kg of CO_2 emissions, or the equivalent of 0.53 passenger cars removed, in climate zone 1A.

5.3 Discussion

The effects of the heating and the cooling load seasons appear to be overshadowed by the electricity and natural gas costs. As a result, due to its high electricity cost, climate zone 8 exhibits energy savings with the cool roof, whereas warmer climate zones, such as 4A, 4C, 6B, and 7, exhibit energy losses with the cool roof and the medium roof.

Overall, when compared to the dark roof, the cool roof and the medium roof produce energy savings and have a positive impact on the environment. However, there were also negatives from the results. The largest reported energy savings reduces the overall energy cost for the homeowner by only 1.93% with the cool roof and only 0.93% with the medium roof.

The environmental impact does appear to be positive for both the cool roof and the medium roof. However, the largest reported CO_2 reduction in this study is 2.52% for the cool roof and 1.23% for the medium roof. Therefore, the roof color changes do not appear to have a significant impact on the CO_2 emissions from the energy used within residential homes in each U.S. climate zone.

A possible concern was that this study did not analyze the deterioration of the cool roof over time. Therefore, the cool roof's energy savings would become lower and, as a result, become even a less attractive option from an economic standpoint.

Also, after the material and labor costs are added, the NPVs suggest that the cool roof and the medium roof are negative investments for a residential home in every U.S. climate zone.

Therefore, the data suggest that the public be informed of the environmental impact for both of these roof colors and the potential annual energy savings. In addition, homeowners should be encouraged to voluntarily paint their homes to alleviate most, if not all, of the upfront costs in order to offset the costs.

5.4 Future research

Several future research opportunities could arise from this study.

An international study could be made of cool roofs on one particular climate zone. Some studies have analyzed the benefits of cool roofs in selected cities throughout the world. However, this study highlights the difference between having a moist, marine, and dry climate within the same climate zone. Therefore, the same philosophy could be applied in an international study by replicating this study with more specific models to international cities within these types of climate zones.

This study represents a general overview of each climate zone with the typical residential model and a given area as defined by the 2009 IECC standard. However, the study could be researched further with multiple locations examined in a given climate zone.

Furthermore, the analysis could illustrate the effects of applying a cool or medium roof to a house built before the 1980s, before the 2000s, and then to the 2006, 2009, or 2012 IECC building standard.

A theoretical analysis could be made if a thermochromic roof were applied to a residential home in a specific climate zone. The analysis could go further by assessing how the thermochromic roof would fare nationally, similarly to how this study investigated medium and cool roofs.

Unfortunately, since neither the cost of a thermochromic roof nor a thermochromic coating has been released to the public, it would be impossible to do an economic analysis at the present time.

Another possible direction for this study would have been to incorporate location-specific government policies. This was generalized with the difference between a cool roof with a premium cost and without the cost. However, different states and regions have policies in place that mitigate some to all of the premium cost.

Energy policies are going to have a huge impact on the future of cool roofs in the world. Therefore, the impact of cool roofs on different types of buildings could be analyzed to determine how to improve building codes such as EnergyStar, Building Energy Rating (BER), and LEED.

Although a medium color was used in this study, it cannot fully replicate the benefits of applying a green, or vegetation, roof to the building. As noted earlier, the green roof was not analyzed because there was too much uncertainty introduced. Therefore, a real-world model could be used for a comparison study between green roofs and cool roofs. Then, several climate zones could be used to determine whether a cool roof is the most viable option.

Albedo degradation of the cool roof was not analyzed in this study. Therefore, future research could be made to determine whether a cool roof would perform better than a dark roof and a medium roof when albedo degradation was applied to it.

Another future research opportunity regards the distribution of the homes in the large-scale U.S. analysis. The National Oceanic and Atmospheric Administration (NOAA) reports that the coastline represents less than 10% of the U.S.'s total land mass but contain 39% of the country's population (The U.S. Population Living, 2014).

Therefore, a staggered analysis could be performed taking into account the population density of each climate zone and adjusting, accordingly, to the total number of households for the analysis.

LIST OF REFERENCES

LIST OF REFERENCES

Akbari, H., Konopacki, S., & Pomerantz, M. (1999). Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. *Energy*, 24, 391-407.

Akbari, H. (2003). Measured energy savings from the application of reflective roofs in two small non-residential buildings. *Energy, 28*, 953-967.

Akbari, H., Levinson, R., & Rainer, L. (2005). Monitoring the energy-use effects of cool roofs on California commercial buildings. *Energy and Buildings*, 37, 1007-1016.

Baechler, M, Williamson, J.L., Gilbride, P.C., Cole, M.G., & Love, P.M. (2010). Building America Best Practices Series Volume 7.1: Guide to Determining Climate Regions by county. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/ba_climateguide_7_1.pdf

Bange, K. (1999). Colouration of tungsten oxide films: A model for optically active coatings. *Solar Energy Materials and Solar Cells*, 58, 1-131.

Bretz, S., & Akbari, H. (1997). Long-term performance of high-albedo roof coatings. *Energy and Buildings, 25*, 159-167.

Building Component Cost Community (2012). BC3 Overview. Retrieved from http://bc3.pnnl.gov/wiki/index.php/Main_Page

Building Sustainability Index (2014, March 5). Solar Absorptance. Retrieved from http://www.basix.nsw.gov.au/basixcms/basix-help-notes/thermal/design-principles2/insulation/roof-solar-absorptance.html

Castleton, H.F., Stovin, V., Beck, S.B.M & Davison, J.B.(2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings, 42*, 1582-1591.

Cheng, M., Miller, W., New, J., & Berdahl, P. (2012). Understanding the long-term effects of environmental exposure on roof reflectance in California. *Construction and Building Materials, 26*, 516-526.

Desjarlais, A.O., Miller, W.A., Bianchi, M.V.A., & Petrie, T.W. (2007).Cool roofs and thermal insulation: energy savings and peak demand reduction. *ASHRAE.*

DOE (2014, January). Status of State Energy Code Adoption. Retrieved from http://www.energycodes.gov/adoption/states

EERE (2008, October).Energy Efficiency Trends in Residential and Commercial Buildings. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

EERE (2010, August).Energy Efficiency Trends in Residential and Commercial Buildings. Retrieved from http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/building_trends_2010.pdf

Efficiency Valuation Organization (2014, February 26). History. Retrieved from http://www.evoworld.org/index.php?option=com_content&view=article&id=40&Itemid=163&lang=en

EIA (2005). Total Consumption by Energy End Uses, 2005 [Data file]. Retrieved from http://www.eia.gov/consumption/residential/data/2005/c&e/summary/pdf/tableus12.pdf

EIA (2009). 2009 Residential Energy Consumption Survey. Retrieved from http://www.eia.gov/consumption/residential/data/2009/

EIA (2013, December). Average price of natural gas sold to residential consumers, by state. Retrieved from http://www.eia.gov/naturalgas/monthly/pdf/table_20.pdf

EIA (2014, January 23). Average price of electricity sold to residential consumers, by state. Retrieved from http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_06_b

Encyclopedia of Earth (2008, August 24). Cool Roofs. Retrieved from http://www.eoearth.org/view/article/151454/

EnergyPlus (2013, October 30). EnergyPlus Energy Simulation Software. Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/

EPA (2012, December 19). Attic & Roof. Retrieved from http://www.epa.gov/greenhomes/attic.htm

EPA (2013, August 29). Cool Roofs. Retrieved from http://www.epa.gov/hiri/mitigation/coolroofs.htm

EPA (2014, May 30). Calculations and References. Retrieved from http://www.epa.gov/cleanenergy/energy-resources/refs.html

Field, K., Deru, M., & Studer, D. (2010, August 11-13). Using DOE Commercial Reference Buildings for Simulation Studies. Paper presented at SimBuild 2010. NREL/CP-550-48588

Fumo, N., Mago, P., & Luck, R. (2010). Methodology to estimate building energy consumption using EnergyPlus benchmark models. *Energy and Buildings, 42*, 2331-2337.

Gentle, A.R., Aguilar, J L.C., & Smith, G.B. (2011). Optimized cool roofs: Integrating albedo and thermal emittance with R-value. *Solar Energy Materials & Solar Cells, 95*, 3207-3215.

Global Cool Cities Alliance (2011). *Cool roofs to cool the world* [PowerPoint slides]. Retrieved from http://coolroofs.org/documents/Exhibit_8-GCCA_Presentation_2011.pdf

Hendron, R. & Engebrecht, C. (2010). Building America house Simulation Protocols. *National Renewable Energy Laboratory*. Retrieved from www.nrel.gov/docs/fy11osti/49246.pdf

Hopkins, A.S., Lekov, A., Lutz, J., & Rosenquist, G. (2011, March). Simulating a Nationally Representative Housing Sample using EnergyPlus. *Lawrence Berkeley National Laboratory*. Retrieved from http://apps1.eere.energy.gov/buildings/energyplus/energyplus_research.cfm

Ichinose, M., Inoue, T., & Sakamoto, Y. (2009). Long-term performance of high-reflectivity exterior panels. *Building and Environment, 44*, 1601-1608.

International Code Council (2014, March 25). About ICC. Retrieved from http://www.iccsafe.org/AboutICC/Pages/default.aspx

International Energy Conservation Code (2014, January 9). IECC Climate Zone Map. Retrieved from http://reca-codes.org/images/ieccmap.jpg

IPMVP (2014, February 18). Concepts and Options for Determining Energy and Water Savings Volume I. Retrieved from http://www.nrel.gov/docs/fy02osti/31505.pdf

Jo, J., Carlson, J.D., Golden, J.S., & Bryan, H. (2010). An integrated empirical and modeling methodology for analyzing solar reflective roof technologies on commercial buildings. *Building and Environment, 45*, 453-460.

Joudi, A., Svedung, H., Cehlin, M., & Ronnelid, M. (2013). Reflective coatings for interior and exterior of buildings and improving thermal performance. *Applied Energy, 103*, 562-570.

Kolokotroni, M., Gowreesunker, B.L., & Giridharan, R. (2011). Cool roof technology in London: An experimental and modeling study. *Energy Buildings*, doi:10.1016/j.enbuild.2011.07.011

Kolokotsa, D., Diakaki, C., Papantoniou, S., & Vlissidis, A. (2012). Numerical and experimental analysis of cool roofs application on a laboratory building in Iraklion, Crete, Greece. *Energy and Buildings, 55*, 85-93.

Konopacki, S., L. Gartland, H. Akbari, and I. Rainer. 1998. Demonstration of Energy Savings of Cool Roofs (PDF). Paper LBNL-40673. Lawrence Berkeley National Laboratory.

Lam, J.C., Tsang, C.L., Li, D.H.W., & Cheung, S.O. (2005). Residential building envelope heat gain and cooling energy requirements. *Energy, 30*, 933-951.

Levinson, R., Akbari, H., & Reilly, J.C. (2007). Cooler tile-roofed buildings with near-infrared-reflective non-white coatings. *Building and Environment, 42*, 2591-2605.

Moody, D., & Sailor, D.J. (2013). Development and Application of a building energy performance metric for green roof systems. *Energy and Buildings, 60*, 262-269.

National Solar Radiation Database (2008, August 20). Typical Meteorological Year 3. Retrieved from http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Net Present Value (NPV) Definition | Investopedia. (2014). *Investopedia*. Retrieved from http://www.investopedia.com/terms/n/npv.asp

Parker, D.S., & Barkaszi, S.F. (1997). roof solar reflectance and cooling energy use: field research results from Florida. *Energy and Buildings, 25*, 105-115.

Payback Period. (2014). *AccountingExplained*. Retrieved from http://accountingexplained.com/managerial/capital-budgeting/payback-period

Peng, T. (2011). MIT Research: Life Cycle Assessment of Residential Buildings. *Concrete Sustainability Report, 6*, 1-2.

Reagan, J.A., & Acklam, D.M. (1979). Solar reflectivity of common building materials and its influence on the roof heat gain of typical southwestern U.S.A residences. *Energy and Buildings, 2*, 237-248.

Responsible Energy Code Alliance (2013, November 2). International Energy Conservation Code. Retrieved from http://reca-codes.org/about-iecc.php.

Responsible Energy Code Alliance (2014, January 10). 2009 International Energy Conservation Code Residential Energy Efficiency. Retrieved from http://reca-codes.org/2009-residential.php

RisMedia (2014). 70 % of affluent homeowners looking to DIY projects to save money. Retrieved from http://rismedia.com/2012-05-10/70-percent-of-affluent-homeowners-looking-to-diy-projects-to-save-money/

Romeo, C., & Zinzi, M. (2011). Impact of a cool roof application on the energy and comfort performance in an existing non-residential building. A Sicilian case study. Energy Buildings, doi:10.1016/j.enbuild.2011.07.023

Saber, H.H., Swinton, M.C., Kalinger, P., & Paroli, R.M. (2012). Long-term hygrothermal performance of white and black roofs in North American climates. *Building and Environment, 50*, 141-154.

Sailor, D.J. (2008). A green roof model for building energy simulation programs. *Energy and Buildings, 40*, 1466-1478.

Scherba, A., Sailor, D.J., Rosenstiel, T.N., & Wamser, C.C. (2011). Modeling impacts of roof reflectivity, photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Building and Environment, 46*, 2542-2551.

Shen, H., Tan, H., & Tzempelikos, A. (2011). The effect of reflective coatings on building surface temperatures, indoor environment, and energy consumption-An experimental study. *Energy and Buildings, 43*, 573-580.

Suehrcke, H., Peterson, E.L., & Selby, N. (2008). Effect of roof solar reflectance on the building heat gain in a hot climate. *Energy and Buildings, 40*, 2224-2235.

Sustainable Housing Guide 5: Building Materials and Insulation for Townsville Homes. (2014). Retrieved from http://www.townsville.qld.gov.au/resident/planning/sustainable/Documents/Sustainable%20Housing%20Guide%205.pdf

Synnefa, A., Santamouris, M., & Akbari, H. (2007). Estimating the effect of using cool coatings on energy loads and thermal comforts in residential buildings in various climatic conditions. *Energy and Buildings, 39*, 1167-1174.

Taylor, Z.T., Fernandez, N., & Lucas, R.G. (2012). Methodology for Evaluating Cost-Effectiveness of Residential Energy Code Changes. U.S. Department of Energy.

The U.S. Population Living at the Coast. (2013, March 14). Retrieved from http://stateofthecoast.noaa.gov/population/welcome.html

Uemoto, K.L., Sato, N.M.N., & John, V.M. (2010). Estimating thermal performance of cool colored paints. *Energy and Buildings, 42*, 17-22.

U.S. BECP (2013, July). Residential Prototype Building Models. Retrieved from http://www.energycodes.gov/development/residential/iecc_models

U.S. Census Bureau (2013, November 1). AHS 2011 National Summary Report and Tables. Retrieved from http://www.census.gov/programs-surveys/ahs/data/2011/h150-11.html

U.S. Census Bureau (2013, December 12). Median and Average Square Feet of Floor Area in New Single-Family Houses Completed by Location. Retrieved from http://www.census.gov/const/C25Ann/sftotalmedavgsqft.pdf

Williams, Jack. *The USA Today weather almanac 1995*. New York: Vintage Books, 1994. Print.

Ye, X., Luo, Y., Gao, X., & Zhu, S.(2012). Design and evaluation of a thermochromic roof system for energy saving based on poly (N-isopropylacrylamide) aqueous solution. *Energy and Buildings, 48*, 175-179.

Zhu, L., Hurt, R., Correa, D., & Boehm, R. (2009). Comprehensive energy and economic analyses on a zero energy house versus a conventional house. *Energy, 34*, 1043-1053.

APPENDICES

Appendix A Single family permits for climate zones

Table A.1

IECC climate zone 1A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Hawaii	**1A**	**Honolulu**	**2203**
Florida	1A	Miami	2045

Table A.2

IECC climate zone 2A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Florida	**2A**	**Tampa**	**27995**
Louisiana	2A	Baton Rouge	7723
Georgia	2A	Savannah	2915
Mississippi	2A	Mobile	1765
Alabama	2A	Mobile	1577
Texas	2A	San Antonio	870

Table A.3

IECC climate zone 2B single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Texas	2B	Houston	44064
Arizona	2B	Phoenix	9409
California	2B	Tucson	102

Table A.4
IECC climate zone 3A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Texas	**3A**	**Wichita Falls**	**15908**
North Carolina	3A	Wilmington	9552
Georgia	3A	Atlanta	9245
South Carolina	3A	Charleston	7979
Oklahoma	3A	Oklahoma City	6864
Alabama	3A	Montgomery	5531
Texas	3A	El Paso	5181
South Carolina	3A	Columbia	4712
North Carolina	3A	Charlotte	3657
Arkansas	3A	Little Rock	3454
Louisiana	3A	Shreveport	2467
Mississippi	3A	Jackson	1769
Alabama	3A	Birmingham	1594
Georgia	3A	Macon	1487
Tennessee	3A	Memphis	1463
Mississippi	3A	Tupelo	893
Arkansas	3A	Shreveport	51
Louisiana	3A	Monroe	20

Table A.5
IECC climate zone 3B single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
California	**3B**	**Los Angeles**	**21167**
Nevada	3B	Las Vegas	4623
New Mexico	3B	Lubbock	953
Utah	3B	Saint George	873
Arizona	3B	Kingman	696
Texas	3B	Fort Worth	314

Table A.6
IECC climate zone 3C single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
California	3C	San Francisco	3585

Table A.7

IECC climate zone 4A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Virginia	**4A**	**Richmond**	**13820**
North Carolina	4A	Raleigh-Durham	12419
Tennessee	4A	Nashville	10167
Maryland	4A	Baltimore	8394
Missouri	4A	St Louis	6660
Kentucky	4A	Lexington	5983

Table A.8

IECC climate zone 4B single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Pennsylvania	**4B**	**Philadelphia**	**3821**
New Mexico	4B	Albuquerque	1282
Texas	4B	Amarillo	636
California	4B	Sacramento	384
Arizona	4B	Prescott	307
Colorado	4B	Trinidad	23
Oklahoma	4B	Amarillo	2

Table A.9

IECC climate zone 4C single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Washington	**4C**	**Seattle**	**10550**
Oregon	4C	Portland	4435
California	4C	Arcata	196

Table A.10
IECC climate zone 5A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Pennsylvania	**5A**	**Harrisburg**	**12472**
Ohio	5A	Columbus	9650
Indiana	5A	Indianapolis	7849
Michigan	5A	Lansing	6041
Illinois	5A	Peoria	5888
Massachusetts	5A	Boston	5839
New York	5A	Albany	5702
Iowa	5A	Des Moines	4956
Connecticut	5A	Hartford	2632
New Jersey	5A	Allentown	2354
New Hampshire	5A	Manchester	1146
Rhode Island	5A	Providence	727
West Virginia	5A	Elkins	657
North Carolina	5A	Elkins WV	419
Missouri	5A	Kirksville	241
South Dakota	5A	Sioux City	171
Maryland	5A	Harrisburg	95
Kansas	5A	Goodland	48

Table A.11
IECC climate zone 5B single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Colorado	**5B**	**Colorado Springs**	**7760**
Utah	5B	Salt Lake City	5084
Washington	5B	Spokane	3889
Nebraska	5B	Omaha	3779
Idaho	5B	Boise	2669
New Mexico	5B	Flagstaff	927
Oregon	5B	Redmond	741
Nevada	5B	Reno	738
Arizona	5B	Flagstaff	343
California	5B	Reno	233
Wyoming	5B	Scottsbluff	18

Table A.12
IECC climate zone 6A single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Wisconsin	**6A**	**Madison**	**6735**
Minnesota	6A	Minneapolis-St Paul	5440
Maine	6A	Portland	2636
New York	6A	Binghamton	2447
South Dakota	6A	Pierre	2015
Michigan	6A	Alpena	1426
Iowa	6A	Mason City	996
Vermont	6A	Burlington	980
North Dakota	6A	Bismarck	789
New Hampshire	6A	Concord	744
Pennsylvania	6A	Bradford	593

Table A.13
IECC climate zone 6B single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Wyoming	**6B**	**Cheyenne**	**1366**
Montana	6B	Helena	1322
Utah	6B	Vernal	926
Idaho	6B	Pocatello	899
Colorado	6B	Eagle	462
Washington	6B	Kalispell	263
California	6B	Eagle	26

Table A.14
IECC climate zone 7 single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Minnesota	**7**	**Duluth**	**1613**
North Dakota	7	Minot	1295
Wisconsin	7	Duluth	952
Alaska	7	Anchorage	601
Colorado	7	Gunnison	545
Michigan	7	Sault Ste Marie	236
Wyoming	7	Jackson Hole	162
Maine	7	Caribou	75

Table A.15
IECC climate zone 8 single-family permits for residential models (Taylor et al. 2012)

State	Climate Zone	TMY3 Location	Single-Family Permits
Alaska	**8**	**Fairbanks**	**65**

Appendix B Housing data

Table B.1
Foundation types percent by state (Hendron et al., 2010)

	Foundation Types			
State	Slab	Heated Basement	Unheated Basement	Crawlspace
Connecticut, Rhode Island, Vermont, New Hampshire, Maine	16.8	23.8	45.5	13.9
Massachusetts	15.8	21.2	51.9	11.2
New York	20.4	25.9	41.7	12
New Jersey	26.9	18.3	30.6	24.2
Pennsylvania	28.9	24.6	32.8	13.7
Illinois	22.5	39.4	14.1	24.1
Ohio and Indiana	27.5	29.9	21.2	21.4
Michigan	15.7	36.2	27.3	20.8
Wisconsin	14.9	45	29.7	10.4
Minnesota, Iowa, North Dakota, South Dakota	22.1	46.9	15.5	15.5
Kansas and Nebraska	29.8	32.7	14.9	22.5
Missouri	24.8	36.4	20.8	17.9
Virginia	33.2	24.2	9.8	32.8
Maryland, Delaware, and West Virginia	28	30.7	18.3	23
Georgia	57.1	6.6	9.7	26.7
North and South Carolina	38.7	2.3	4.1	54.9
Florida	87.7	0	0.4	11.8
Alabama, Mississippi, Kentucky	44.1	8.6	10.6	36.7
Tennessee	35.3	7.2	9	48.4
Arkansas, Louisiana, and Oklahoma	66.9	0.6	2.9	29.7
Texas	79.6	0.3	0.4	19.8
Colorado	30.7	28.2	9.9	31.2
Utah, Wyoming, Montana, Idaho	26.7	36.6	11	25.6
Arizona	90.7	0.6	3.1	5.6
Nevada and New Mexico	86.1	2.5	0.8	10.7
California	59	1.2	4.9	34.9
Washington, Oregon, Alaska, Hawaii	37	8.9	3.1	51

Table B.2

Heating system by percentage for census divisions (Hendron et al., 2010)

Census Division	Electric Heat Pump	Gas Heating	Oil Heating	Electric Furnace
New England	10.8	57	31.1	1.1
Middle Atlantic	24.5	69.2	4.6	1.7
East North Central	22.5	76.2	0.5	0.7
West North Central	39.6	56.7	0.2	3.4
South Atlantic	78.9	19	0.1	2
East South Central	68.9	28.9	0	2.1
West South Central	37.5	48.1	0	14.5
Mountain	19.4	77.8	0.2	2.6
Pacific	34	62.9	0.2	2.9

Table B.3

Climate zone, location, heating source, and foundation

Climate Zones	Location	Heating Source	Foundation
1A	Honolulu, HI	Gas Heating	Crawlspace
2A	Tampa, FL	Electric Heat Pump	Slab
2B	Houston, TX	Gas Heating	Slab
3A	Wichita Falls, TX	Gas Heating	Slab
3B	Los Angeles, CA	Gas Heating	Slab
3C	San Francisco, CA	Gas Heating	Slab
4A	Richmond, VA	Electric Heat Pump	Slab
4B	Philadelphia, PA	Gas Heating	Unheated Basement
4C	Seattle, WA	Gas Heating	Crawlspace
5A	Harrisburg, PA	Gas Heating	Unheated Basement
5B	Colorado Springs, CO	Gas Heating	Crawlspace
6A	Madison, WI	Gas Heating	Heated Basement
6B	Cheyenne, WY	Gas Heating	Heated Basement
7	Duluth, MN	Gas Heating	Heated Basement
8	Fairbanks, AK	Gas Heating	Crawlspace

This appendix contains information of the foundations and heating systems used by percentage in each state.

Appendix C Occupancy Schedules

This appendix depicted the occupancy schedules for the IECC models. The figures were created based on the data for the occupancy schedules included for each model.

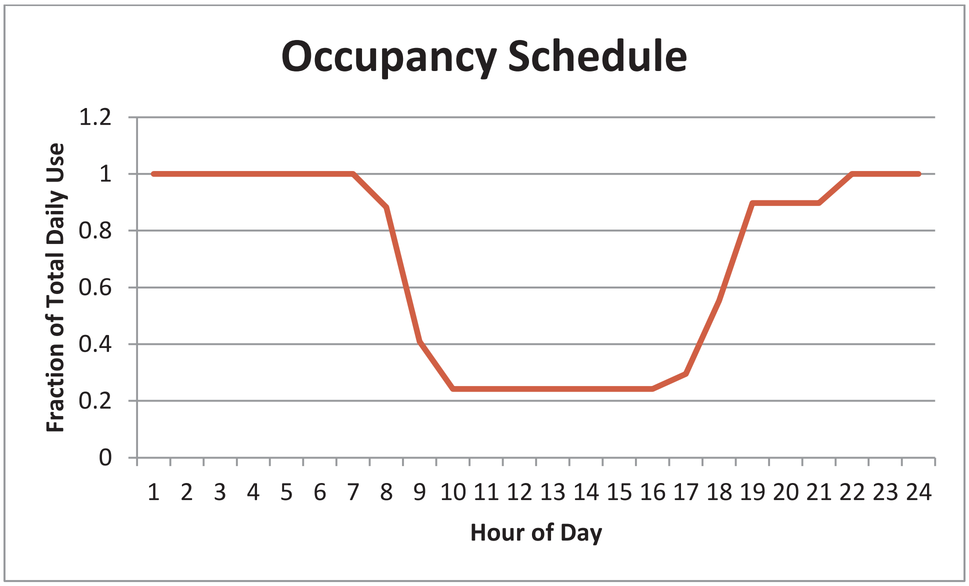


Figure C.1 Daily occupancy schedule (Hendron et al., 2010)

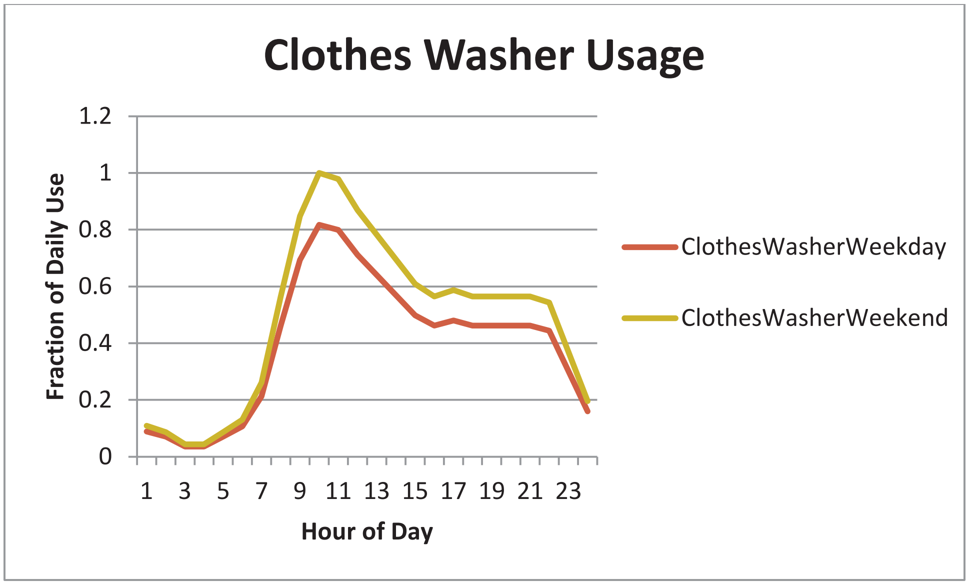


Figure C.2 IECC model clothes washer occupancy schedule (Hendron et al., 2010)

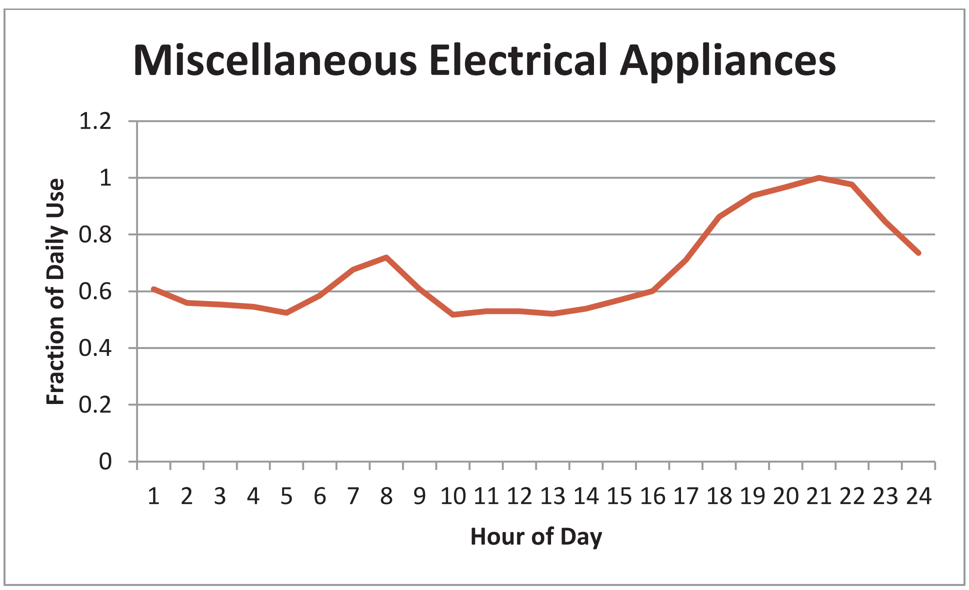


Figure C.3 IECC model miscellaneous electrical appliances occupancy schedule (Hendron et al., 2010)

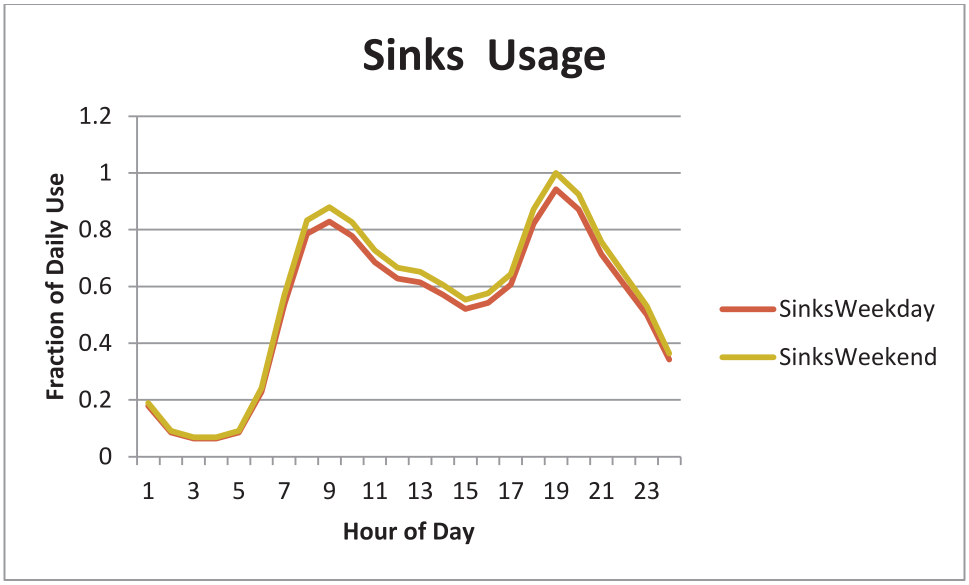


Figure C.4 IECC model sinks occupancy schedule (Hendron et al., 2010)

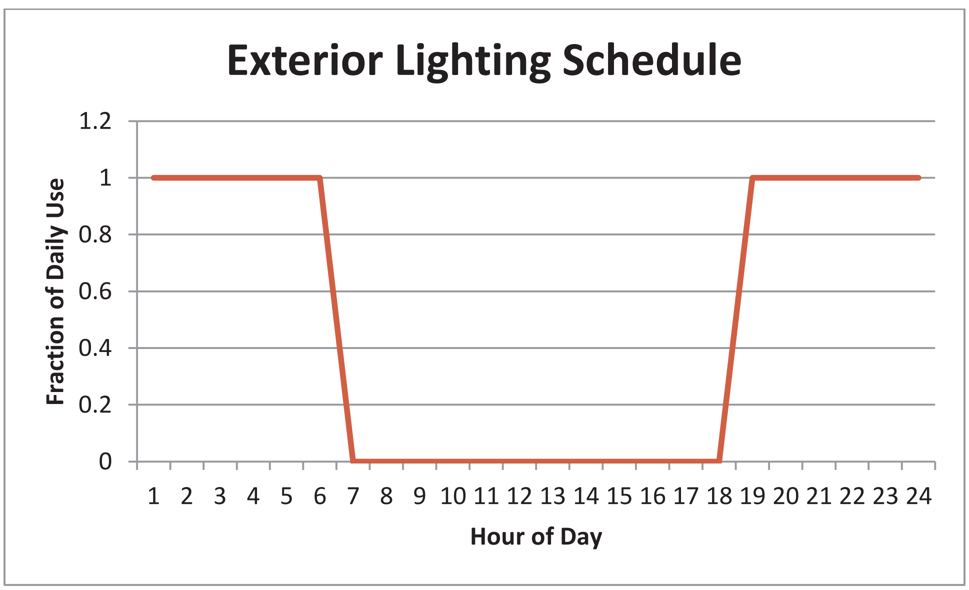


Figure C.5 IECC model exterior lighting occupancy schedule (Hendron et al., 2010)

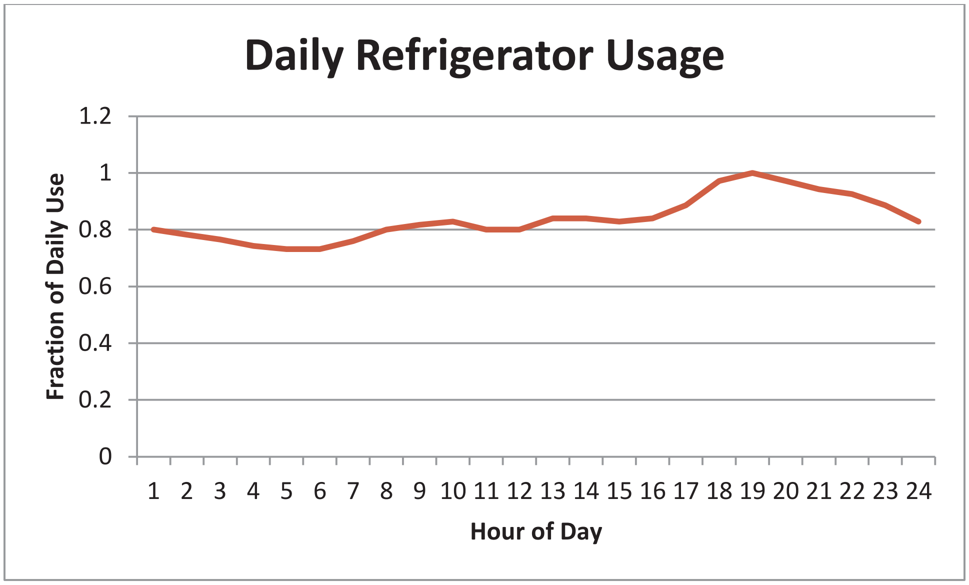


Figure C.6 IECC model daily refrigerator occupancy schedule (Hendron et al., 2010)

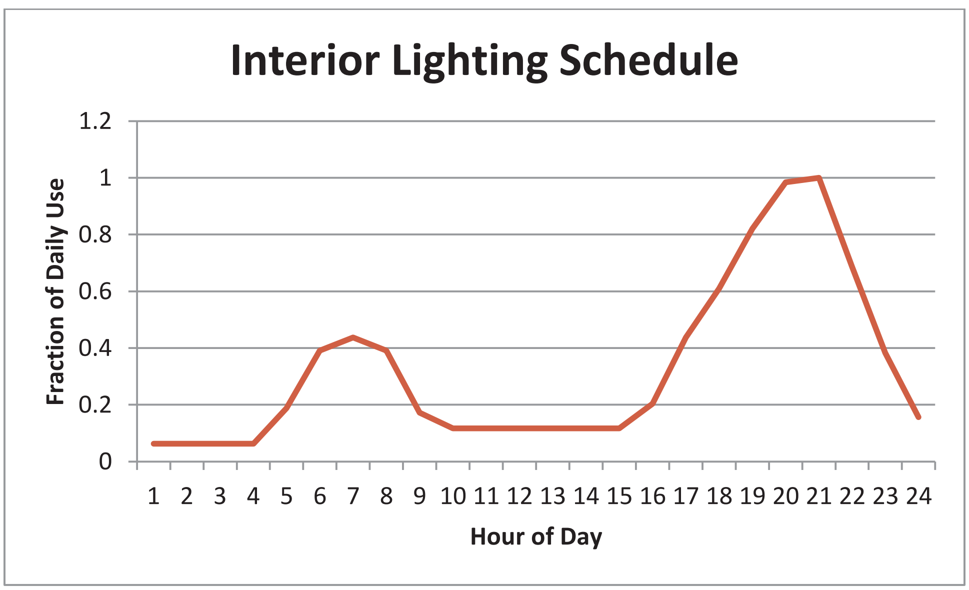


Figure C.7 IECC model interior lighting occupancy schedule (Hendron et al., 2010)

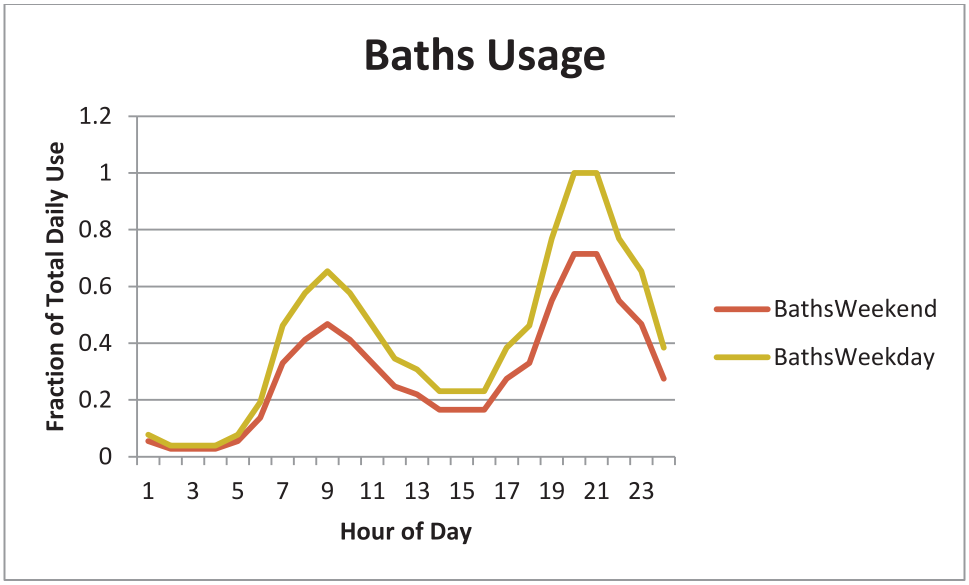


Figure C.8 IECC model baths occupancy schedule (Hendron et al., 2010)

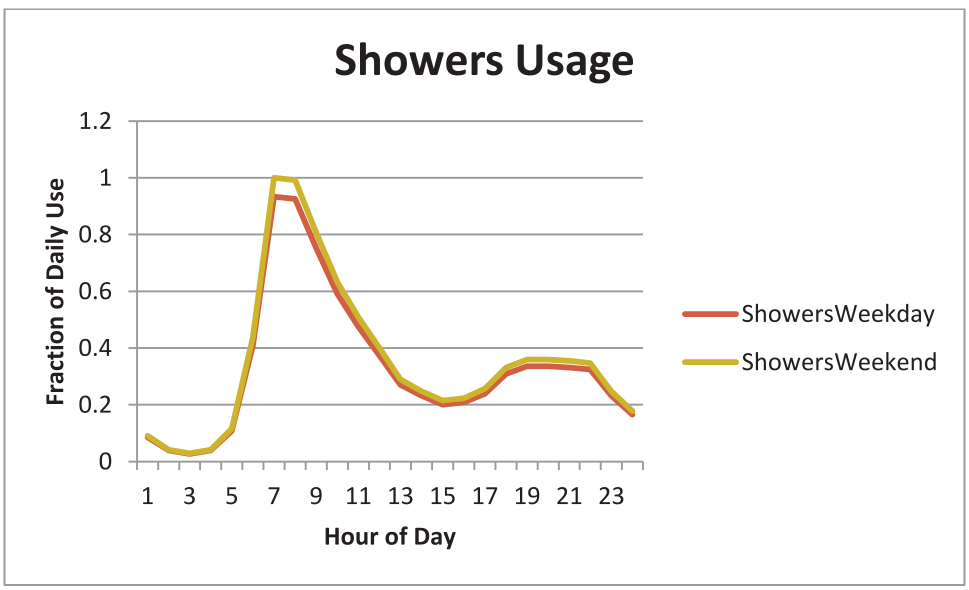


Figure C.9 IECC model shower occupancy schedule (Hendron et al., 2010)

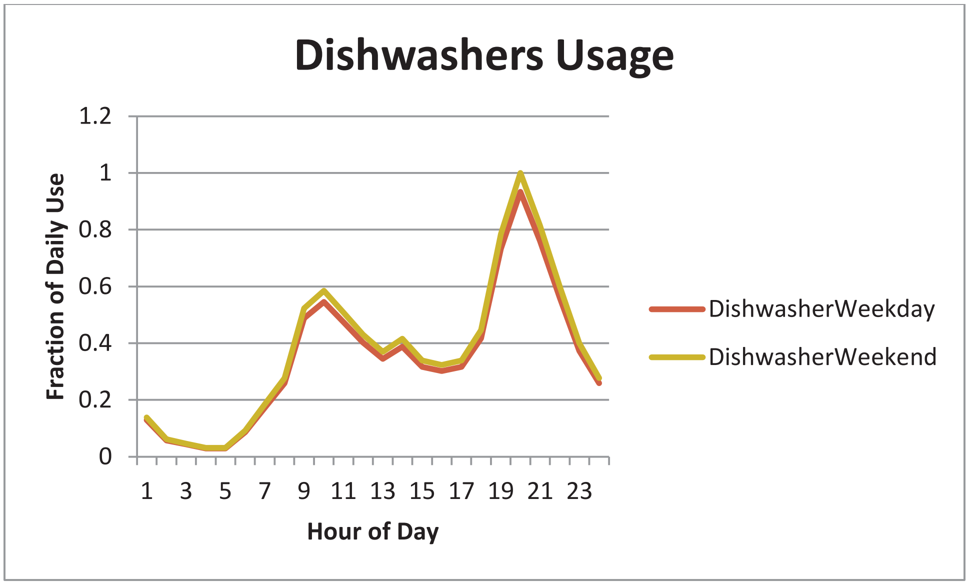


Figure C.10 IECC model dishwasher occupancy schedule (Hendron et al., 2010)

Table C.1

Insulation and fenestration requirements by component (Responsible Energy Code Alliance, 2014)

Climate Zone	Fenestration U-factor	Glazed fenestration SHGC	Ceiling R-value	Wood frame wall R-value
1	1.2	0.3	30	13
2	0.65	0.3	30	13
3	0.5	0.3	30	13
4 (except marine)	0.35	NR	38	13
5 and zone 4 marine	0.35	NR	38	20
6	0.35	NR	49	20
7 and 8	0.35	NR	49	21

Table C.2

Insulation and fenestration requirements by component (contd.)
(Responsible Energy Code Alliance, 2014)

Climate Zone	Mass wall R-value	Floor R-value	Basement Wall R-value	Slab R-value & depth	Crawl space wall R-value
1	3/4	13	0	0	0
2	4/6	13	0	0	0
3	5/8	19	5/13	0	5/13
4 (except marine)	1/2	19	10/13	10, 2 ft	10/13
5 and zone 4 marine	13/17	30	10/13	10, 2 ft	10/13
6	15/19	30	15/19	10, 4 ft	10/13
7 and 8	19/21	30	15/19	10, 4 ft	10/13

Appendix D Electricity & natural gas consumption

Table D.1

Annual electricity consumption (kWh)

	Color Coatings		
Climate Zones	Cool Roof	Medium Roof	Dark Roof
1A	17,096	17,288	17,471
2A	20,509	20,662	20,805
2B	13,965	14,128	14,279
3A	13,420	13,557	13,688
3B	9,905	10,037	10,163
3C	9,400	9,475	9,547
4A	29,173	29,165	29,158
4B	11,810	11,910	12,003
4C	9,919	9,998	10,072
5A	11,646	11,746	11,838
5B	10,842	10,952	11,056
6A	11,153	11,206	11,257
6B	10,405	10,449	10,494
7	10,392	10,427	10,460
8	10,532	10,567	10,599

Table D.2

Annual natural gas consumption (Therms)

	Color Coatings		
Climate Zones	Cool	Medium	Dark
1A	168	168	168
2A	0	0	0
2B	444	441	439
3A	718	714	710
3B	376	373	370
3C	648	640	634
4A	0	0	0
4B	974	968	963
4C	811	804	798
5A	1,121	1,115	1,109
5B	941	933	925
6A	1,420	1,414	1,408
6B	1,236	1,230	1,223
7	1,757	1,751	1,744
8	2,322	2,317	2,311

Appendix E Energy costs and results

This appendix contains the annual electricity cost, natural gas cost, electricity results, and natural gas results for this study.

Table E.1
Annual electricity cost ($)

	Color Coatings		
Climate Zones	Cool	Medium	Dark
1A	$6,410.98	$6,483.07	$6,551.70
2A	$2,335.97	$2,353.44	$2,369.74
2B	$1,531.95	$1,549.86	$1,566.42
3A	$1,472.20	$1,487.24	$1,501.62
3B	$2,061.34	$2,082.41	$2,102.54
3C	$1,521.48	$1,541.71	$1,561.06
4A	$3,261.59	$3,260.65	$3,259.86
4B	$1,509.34	$1,522.03	$1,533.98
4C	$845.14	$851.83	$858.10
5A	$1,488.40	$1,501.10	$1,512.92
5B	$1,247.97	$1,260.62	$1,272.52
6A	$1,478.95	$1,485.98	$1,492.68
6B	$1,021.76	$1,026.12	$1,030.50
7	$1,187.85	$1,191.81	$1,195.59
8	$1,905.32	$1,911.55	$1,917.35

Table E.2
Annual natural gas cost ($)

Climate Zones	Color Coatings: Cool	Medium	Dark
1A	$868.66	$868.44	$868.22
2A	N/A	N/A	N/A
2B	$458.21	$455.27	$452.56
3A	$740.34	$736.09	$732.09
3B	$336.20	$333.29	$330.74
3C	$578.81	$572.07	$566.01
4A	N/A	N/A	N/A
4B	$1,141.48	$1,134.73	$1,128.39
4C	$940.75	$933.16	$926.17
5A	$1,314.01	$1,306.60	$1,299.72
5B	$764.25	$757.53	$751.30
6A	$1,286.38	$1,281.11	$1,276.12
6B	$1,017.36	$1,012.09	$1,006.97
7	$1,374.33	$1,369.04	$1,364.00
8	$1,922.90	$1,917.97	$1,913.49

Table E.3
Annual overall energy cost ($)

Climate Zones	Overall energy cost
1A	$7,419.92
2A	$2,369.74
2B	$2,018.98
3A	$2,233.71
3B	$2,433.27
3C	$2,127.07
4A	$3,259.86
4B	$2,662.38
4C	$1,784.27
5A	$2,812.64
5B	$2,023.82
6A	$2,768.80
6B	$2,037.47
7	$2,559.59
8	$3,830.84

Table E.4
Annual electricity savings compared to dark roof($)

All Climate Zones	Cool Roof	Medium Roof
1A	$140.72	$68.62
2A	$33.77	$16.31
2B	$34.47	$16.56
3A	$29.42	$14.37
3B	$41.19	$20.13
3C	$39.58	$19.35
4A	-$1.73	-$0.79
4B	$24.64	$11.95
4C	$12.96	$6.27
5A	$24.52	$11.83
5B	$24.55	$11.90
6A	$13.73	$6.70
6B	$8.74	$4.39
7	$7.74	$3.79
8	$12.03	$5.80

Table E.5
Annual natural gas financial losses ($)

All Climate Zones	Cool Roof	Medium Roof
1A	-$0.44	-$0.22
2A	N/A	N/A
2B	-$5.66	-$2.71
3A	-$8.25	-$4.00
3B	-$5.46	-$2.56
3C	-$12.81	-$6.06
4A	N/A	N/A
4B	-$13.08	-$6.34
4C	-$14.58	-$6.99
5A	-$14.29	-$6.88
5B	-$12.96	-$6.23
6A	-$10.26	-$5.00
6B	-$10.40	-$5.13
7	-$10.33	-$5.04
8	-$9.41	-$4.48

Table E.6

Annual energy savings compared to dark roof($)

Climate Zones	Cool	Medium
1A	$140.72	$68.62
2A	$33.77	$16.31
2B	$34.47	$16.56
3A	$29.42	$14.37
3B	$41.19	$20.13
3C	$39.58	$19.35
4A	-$1.73	-$0.79
4B	$24.64	$11.95
4C	$12.96	$6.27
5A	$24.52	$11.83
5B	$24.55	$11.90
6A	$13.73	$6.70
6B	$8.74	$4.39
7	$7.74	$3.79
8	$12.03	$5.80